Irrigation control system with a web-based interface for the management of *Eucalyptus* planting stock

by

Nkosinathi David Kaptein
B.Sc. Hons. (Environmental Science), University of KwaZulu-Natal

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School of Agricultural, Earth and Environmental Sciences
College of Agriculture, Engineering and Science
University of KwaZulu-Natal
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PREFACE

The research contained in this dissertation was completed by the candidate while based in the Discipline of Agrometeorology, School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa. The research was financially supported by the Institute for Commercial Forestry Research.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

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Nkosinathi David Kaptein

Date: _________________________

Supervisor

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Professor Michael J Savage

Date: _________________________

Co-supervisor

____

Dr Marnie E Light

Date: _________________________

DECLARATION

I, Nkosinathi David Kaptein, declare that:

(i) the research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work;

(ii) this dissertation has not been submitted in full or in part for any degree or examination to any other university;

(iii) this dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

(iv) this dissertation does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

a) their words have been re-written but the general information attributed to them has been referenced;

b) where their exact words have been used, their writing has been placed inside quotation marks, and referenced;

(v) where I have used material for which publications followed, I have indicated in detail my role in the work;

(vi) this dissertation is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

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EXTENDED ABSTRACT

Commercial forestry nurseries use large quantities of water to irrigate the planting stock to meet the annual forestry industry planting demands. However, South Africa is a water scarce country and there is high competition for this limited resource with other sectors. Thus, sustainable water management strategies should be put in place to preserve this precious resource. In commercial forestry nurseries, sustainable water use may be achieved by carefully managing irrigation schedules, such as accurately measuring growing media water content and then replenishing the depleted soil water. Improved nursery irrigation management may not only save water, but also has the potential to reduce the prevalence of pests and diseases, excessive leaching of nutrients, irrigation costs and may produce robust planting stock that is better suited to adapt to field conditions.

Growing media water content can be directly measured by the gravimetric method. However, this method is laborious, time consuming, costly and does not allow for near real-time monitoring and control. Several indirect methods for estimating soil water content have been developed and are in use today. Some common methods are: frequent domain reflectometry, time domain reflectometry, time domain transmission and the dual-needle heat pulse method. However, each method has advantages and disadvantages. Considerations for choosing the most appropriate method are the ability to automate, accuracy and precision, skills required to use and the costs to purchase.

The main objective of this study was to calibrate the low cost commercially available Decagon EC-5 soil water content sensors using nursery growing media. The calibration equation was then used to measure and control irrigation for *Eucalyptus grandis* x *Eucalyptus urophylla* and *Eucalyptus dunnii* planting stock grown in seedling trays in a greenhouse. A web-based data and information system was utilised to share measurements and display greenhouse environmental conditions in near real-time. The data could be viewed or downloaded using the internet[1].

Decagon EC-5 soil water content sensors were laboratory-calibrated, using nursery growing media, against the standard gravimetric method. Four nursery growing media were used for calibrations: coir/perlite mix (CP), coir/pine bark/vermiculite mix (CPBV), pine bark (PB) and sandy soil. The calibration relationships between gravimetric water content and sensor output for each growing media were established, and the manufacturer supplied calibration equation was evaluated against laboratory calibration equations. The appropriate laboratory calibration equation was programmed in the datalogger to measure and control irrigation. Greenhouse microclimate measurements of air temperature, relative humidity and solar irradiance were conducted. Hourly grass reference evaporation

[1] http://agromet.ukzn.ac.za:5355/?command=RTMC&screen=ICFR%20Greenhouse

(ETo) was calculated by the datalogger. The greenhouse microclimate measurements were compared against an open area automatic weather station at the University of KwaZulu-Natal Agrometeorology Instrumentation Mast (UKZN AIM) system measurements.

The EC-5 soil water content sensors were used to schedule irrigation for *E. grandis* x *E. urophylla* hybrid clones (GxU) (Experiment 1) and *E. dunnii* seedlings (Experiment 2) grown in seedling trays inside a fully air temperature controlled greenhouse. Irrigation was controlled in three treatments: low, medium and high watering. All treatments were treated the same except for differing irrigation application. Total daily irrigation and drainage were measured per treatment. Irrigation scheduling for GxU was programmed at a set point and *E. dunnii* seedlings at lower and drained upper limits. Seedling measurements conducted were root collar diameter (RCD), heights, stomatal conductance (g_s), root-to-shoot ratio and total leaf area. Total drainage and its electrical conductivity (EC) was also measured.

The calibration relationship showed a linear relationship between gravimetric water content and sensor output for all four growing media with an R^2 greater than 0.92. The manufacturer supplied calibration equation poorly estimated growing media water content compared to the laboratory calibration. Poor estimation exceeded the 5% error specified by the manufacturer.

Air temperature was consistently less than 25°C inside the greenhouse. The external air temperature, as measured by the UKZN AIM system, fluctuated and reached a maximum of 36.6°C during the study period. Solar irradiance inside the greenhouse was 60% lower than that measured by the UKZN AIM system. The relative humidity was consistently higher inside the greenhouse compared to that measured by the UKZN AIM system. Greenhouse grass reference evaporation was consistently lower than the UKZN AIM system due to low air temperature and high RH inside the greenhouse.

For Experiment 1, the GxU clones were irrigated too frequently for short periods. This led to over- and under- irrigation in high and low watering treatments, respectively. However, these challenges were addressed in Experiment 2 using *E. dunnii* seedlings irrigated at lower and drained upper irrigation limits. In Experiment 2, variability in sensor measurements within each treatment were observed at drained upper limit and decreased at lower limit. This was likely caused by a change in the pore space volume from dry to wet growing media. The web-based system was successfully used as an early warning system to monitor soil water content measurements and greenhouse microclimate, averting experimental failure due to lack of irrigation on one occasion.

Seedlings in the high watering treatment had the highest RCD, heights and g_s followed by the medium and low watering treatments. Although the low watering treatment had the lowest growth rates and g_s these seedlings were more robust, hardy and resistant to water stress. The root-to-shoot ratio showed no statistically significant differences between treatments. However, seedlings in the high watering treatment had slightly greater root volume. This was probably due to the increased total seedling leaf area for this treatment which facilitated increased photosynthetic activity and carbohydrates production, enabling increased root growth. The highest EC measurements were recorded in the low watering treatment. This was likely due to low irrigation and therefore nutrients were not washed off the growing media. Medium watering treatment EC was 30% lower than the low watering treatment whilst high watering EC was almost equivalent to the irrigation water.

The analysis of economics showed that implementing the fully automated system could be costly. However, there are many potential benefits that may be offered by this system such as reduction in water use, pumping costs and management time. The early warning offered by this system could potentially help avoid the loss of planting stock if there is a problem with the irrigation system.

The study showed that irrigation may be automatically scheduled for nursery seedlings trays using low cost Decagon EC-5 soil water content sensors with reasonable accuracy. However, medium-specific calibration is important to improve the soil water content measurement accuracy. The study also showed that reducing irrigation may result in reduced growth rates of seedlings. However, other benefits such as seedling resistance to water stress, robust seedlings, irrigation water savings and a reduction in washing off nutrients may be achieved.

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LIST OF ABBREVIATIONS

AC	Alternating current
AWS	Automatic weather station
CP	Coir/perlite media mix
CPBV	Coir/pine bark/vermiculite media mix
DC	Direct current
DUL	Drained upper limit
DNHP	Dual needle heat pulse
DOY	Day of year
EC	Electrical conductivity
ETo	Reference evaporation
FDR	Frequency domain reflectometry
FTP	File transfer protocol
g_s	Stomatal conductance
GxU	*Eucalyptus grandis* x *Eucalyptus urophylla* hybrid cross
ICFR	Institute for Commercial Forestry Research
LL	Drained lower limit
PAW	Plant available water
PB	Pine bark
PLC	Programmable logic controller
R^2	Regression co-efficient
RCD	Seedling Root collar diameter
RGP	Root growth potential
RMSE	Root mean square error
SD	Standard deviation
SE	Standard error
TDR	Time domain reflectometry
TDT	Time domain transmission
UKZN AIM	University of KwaZulu-Natal Agrometeorology Instrumentation Mast
θ_v	Volumetric water content

CHAPTER 1: INTRODUCTION

1.1 Motivation for the study

Water is generally the most limiting factor in agriculture and the forestry industry worldwide. South Africa is classified as a semi-arid country, receiving an average annual rainfall of 560 mm (Department of Environmental Affairs, 2012). Spatially, rainfall is not evenly distributed and is mostly sporadic and erratic varying from year to year. This results in unpredictable drought and flooding periods which may directly affect commercial forestry yields which rely entirely on precipitation (Department of Environmental Affairs, 2012).

Commercial hardwood plantations such as *Eucalyptus* spp. play a crucial role in the South African forestry industry for the production of pulp and cellulose for the paper industry. Furthermore, *Eucalyptus* are also used for the production of charcoal, furniture and poles (Silva *et al*., 2012). In South Africa, *Eucalyptus* spp. occupy a total area of 541 000 ha of the total 1.5 million ha of commercial forestry (Albaugh *et al*., 2013). They contribute 1.2% to GDP through employment and exports. The use of commercially planted *Eucalyptus* spp. alleviates the pressure on the use of indigenous forests and associated impacts on natural biodiversity. The relative ease of establishment and rapid growth over a wide range of site conditions, along with the ability of many *Eucalyptus* spp. to readily coppice are all favourable attributes (Albaugh *et al*., 2013).

South African commercial forestry nurseries use large quantities of irrigation water per year to produce 241 million *Eucalyptus* planting stock needed to re-establish commercial forestry sites (Albaugh *et al*., 2013). Regardless of the important economic role of *Eucalytus* spp. in South Africa, water shortage is a limiting factor due to increased demand for this limited resource for household, industrial and agricultural uses. As water becomes scarcer, the cost of water increases thereby adding pressure on commercial forestry nurseries in producing planting stock. The pressing issue of water shortage compelled the Department of Agriculture Forestry and Fisheries to implement the South African National Water Act of 1998 which is aimed at charging and allocating water resources equitably (Department of Environmental Affairs, 2012). This implies that water conservation measures need to be implemented by commercial forestry nurseries through correct irrigation scheduling.

It is important for commercial forestry nurseries to produce high quality *Eucalyptus* planting stock to meet annual planting requirements by the forestry industry. High quality planting stock is characterised by good morphological, physiological and nutritional traits which are influenced by good nursery management practices such as correct irrigation scheduling (Silva *et al*., 2012). Correct irrigation enhances planting stock quality through better osmotic adjustment, better root growth, improved transpiration rates and seedlings that are more resistant to water stress and frost (McDonald, 1984; Salvador *et al*., 1999). Irrigation scheduling should be designed to keep a correct balance of water and air in the growing medium so that seedlings are not over-irrigated nor water stressed (McDonald, 1984). Over-irrigation may cause waterlogged conditions, excessive leaching of nutrients and may lead to an environment conducive to pests and diseases, hence affecting seedling quality (Salvador *et al*., 1999; Gindaba *et al*., 2004). In addition, excessive irrigation leads to water wastage. Contrarily, under-irrigation is visible through morphological symptoms such as wilting followed by biochemical changes resulting in, amongst others the closing of stomata and the seedling may eventually die. Seedlings may acclimatise to water stress conditions leading to slower growth rates due to restriction in the expansion of plant cells and reduction in carbon assimilation (Silva *et al*., 2004).

Most nurseries, particularly commercial nurseries, generally set their irrigation at fixed time schedules. Irrigation is set at six to eight fixed frequencies of four to ten min per day depending on the stage of seedling growth and season of the year (van der Westhuizen, 2009). Forestry nurseries in South Africa generally use pine bark as a growing medium for *Eucalyptus* seedlings, since it has easily available soil water defined as the difference between drained upper limit and lower limit water content (van der Weisthuizen, 2009). Pine bark is however, characterised by low water holding capacity compared to other growing media (van der Westhuizen, 2009). This increases the risk of water stress to seedlings, particularly during the stage of high growth vigour. This means that pine bark needs to be irrigated slowly but more frequently to keep the media water content high. Fricke (1998) found that tomatoes grown in pine bark medium needed to be over-irrigated by 20 to 30% per irrigation schedule to avoid the risk of water stress and to flush out salt accumulation in the medium. Recently, coir mixed with other media substrates are commonly used in most commercial forestry nurseries since coir has a high water holding capacity (SA Forestry Magazine, 2014). Plants grown in coir tend to be over-irrigated because nursery managers irrigate coir similarly to pine bark (van der Westhuisen, 2009). Unlike pine bark that needs to be irrigated frequently with large quantities of water, coir needs to be irrigated less frequently with small quantities of water. Adequate watering of coir may improve the air filled porosity and reduce the risk of pests and diseases. Measuring and controlling growing media water content using an automated irrigation system might assist in addressing the problem of inadequate watering. However, automated irrigation systems may be costly. Therefore understanding implementation costs and benefits that these systems may offer is important.

A number of techniques have been developed and used over time to measure and control irrigation scheduling. Gebregiorgis and Savage (2006a) reported that the ideal system for measuring and controlling soil water content should be quick, accurate and precise, inexpensive and simple to use. Traditional methods to determine timing of irrigation scheduling required pre-determined values of field capacity, refill and wilting points for soil water content or water potential (Lukanu and Savage, 2006).

These methods also need the actual soil water content to be determined using the gravimetric method to forecast the next date of irrigation (Chanzy *et al*., 1998; Gebregiorgis and Savage, 2006a). There are many different methods that can be used to measure soil water content such as the gravimetric (direct) method and other indirect methods such as neutron probe, frequent domain reflectometry (FDR), time domain reflectometry (TDR) and time domain transmission (TDT) (Murnoz-Carpena, 2004; Gebregiorgis and Savage, 2006a). Soil water potential may be indirectly measured by tensiometers, thermocouple psychrometers, heat dissipation and electrical resistance sensors. The gravimetric method is not ideal since it is time consuming, needs repeated sampling, causes soil disturbance and can not be automated. The neutron probe method is more ideal. However, it involves radioactive material which requires licensing and training of users. It is also restrictive since it does not allow unattended measurements of soil water content (Annandale *et al*., 2011). Tensiometers and heat dissipation sensors meet some of the requirements. However, they cover a limited range of soil water potential. Watermark and electrical resistance sensors meet most of the requirements; the limitations are that they are affected by soil temperature, have low resolution and react slowly to changes in soil water potential. Thermocouple psychrometers are almost ideal but they require calibration for good accuracy, are thermally sensitive and problematic if irrigation is applied (Savage and Cass, 1984; Baumhardt *et al*., 2000).

In recent years, the high dielectric permittivity of water relative to other soil particles at high frequencies has been used as a foundation to measure soil water content. The FDR, TDR and TDT sensors measure the dielectric permittivity of soil which can be converted to soil water content using the Topp *et al*. (1980) empirical equation. These techniques offer precise, non-destructive and unattended *in situ* measurements of soil water content. Usually the manufacturers of these sensors provide a factory calibration equation for general soils for converting dielectric permittivity to voltage and then to soil water content. For FDR, the manufacturer recommends a soil specific calibration to increase the accuracy of soil water measurement, for example, commercially available capacitance sensors. Once the sensors are calibrated, the soil water content limits need to be defined (drained upper and lower limits) in the laboratory. Gebregiorgis and Savage (2006b) reported that the drained upper and lower limits can be estimated from an empirical equation based on the measurements of soil properties such as soil texture, bulk density and organic matter content. In the laboratory, the lower limit can be estimated using pressure cells at -1500 kPa, whereas the drained upper limit can be estimated at -10 kPa for coarse textured soil and -33 kPa for fine textured soil (Gebregiorgis and Savage, 2006b). Ladson *et al*. (2004) reported that the lower and drained upper limits could be estimated using the soil water content time series data. The driest measurement in the time data series could be estimated as the lower limit (*LL*) and the wettest measurement the drained upper limit (*DUL*). Estimation using this method requires a reliable data set and the need to accurately measure the depth of soil water content measurements.

There have been very few studies using an automated irrigation system to measure and control the soil water content of containerised seedlings. In this study, FDR sensors will be used to estimate the growing media water content of seedling trays and schedule irrigation based on the measured soil water content.

1.2 Aims and objectives

The overall aim of this study was to develop a growing media water content online sensor network linked to an automated irrigation system to measure and schedule irrigation for containerised *Eucalyptus* seedlings and *Eucalyptus* clones in a greenhouse. Specific objectives included:

- calibrate low cost commercially available Decagon EC-5 soil water content sensors against the gravimetric method to measure growing media water content of seedling plugs;
- develop an automated irrigation system to measure and control growing media water content of *E. grandis* x *E. urophylla* hybrid clonal cutting and *E. dunnii* seedling plugs;
- compare growth and development of *E. dunnii* seedlings subjected to different water regimes.

1.3 Thesis structure

Chapter 1 provides an introduction to the study with an overview of commercial forestry nurseries. Different indirect methods of measuring soil water content that have been successfully used for different applications are also introduced.

Chapter 2 provides some information on production of forestry planting stock and focuses on the theoretical background of measuring soil water content and its relationship with soil water potential. In-depth details of different methods for measuring soil water content and potential are explained.

Chapter 3 focuses on the laboratory calibration of Decagon EC-5 soil water content sensors against the gravimetric method. The detailed calibration procedure is presented and statistical tools used in analysing the data. The relationship between sensor output and volumetric water content is presented. Also, the manufacturer supplied equation is evaluated against the laboratory calibration equation.

In Chapter 4 the ICFR greenhouse microclimate and the outside microclimates were compared using the open area UKZN AIM system. Also the viability of Decagon EC-5 soil water content sensors in measuring and controlling irrigation for forestry nursery seedling trays is investigated. The growth rates of seedlings subjected to different watering regimes are tested. Analysis of economics for an automated irrigation system is conducted.

Chapter 5 is the summary of the conclusions and recommendation for future research.

CHAPTER 2: LITERATURE REVIEW

2.1 *Eucalyptus* spp. planting stock quality

In South Africa, *Eucalyptus* is mostly grown in summer rainfall regions along the eastern seaboard of the country and its adjacent escarpments, particularly in KwaZulu-Natal and Mpumalanga. *Eucalyptus* grows optimally in sites that receive rainfall greater than 800 mm per annum with a mean annual air temperature of 18°C (Rolando and Little, 2008). Rainfall in these regions varies from 700 to 1200 mm per annum, with the mean annual air temperature ranging between 14 and 22°C (South and Zwolinski, 1997). Even when *Eucalyptus* planting stock is planted at optimum growing sites, post planting mortality of more than 10% is often experienced due to extreme air temperatures, solar irradiance and wind speed (Rolando and Little, 2008). Improving the quality of the *Eucalyptus* planting stock at the nursery may result in robust seedlings that are more resistant to harsh field conditions (Salvador *et al*., 1999). A reduction in post-planting mortality is important for reaching the target stem density and reducing costs of re-planting dead and poor growing plants (Rolando and Little, 2008).

The planting stock quality index is determined by good morphological and physiological measures which to a greater extent may be achieved through good nursery management practices such as proper irrigation scheduling, fertilisation and other cultural practices (Salvador *et al*., 1999; Rolando and Little, 2008). The most commonly used planting stock measures for morphological attributes are: root collar diameter (RCD), height, bud diameter and root-to-shoot ratio (Rolando and Little, 2008). These measures may be measured by digital caliper, a ruler and destructive harvesting of the planting stock. Physiological measures are: root growth potential (RGP), stomatal conductance (g_s) and leaf photosynthesis. Stomatal conductance and leaf photosynthesis may be measured by steady state leaf porometers. The RGP is measured by destructively harvesting the planting stock and measuring the spread and the amount of root growth. It offers some indication of the physiological status of the planting stock since it provides an indication of the potential root growth in the period following transplanting (South and Zwolinski, 1997; Rolando and Little, 2008; Silva *et al*., 2012). Morphological and physiological measures are mostly influenced by correct irrigation scheduling of the planting stock. In a study by Salvador *et al*. (1999) on planting stock water stress relations, correct irrigation scheduling increased the seedling osmotic adjustment, cell wall elasticity and root growth capacity in-field. Transpiration rates were reduced causing planting stock to be more resistant to water stress.

2.2 Forestry nursery growing media

A well formulated growing media should have ideal properties such as: high water holding capacity, high aeration porosity, free from pests, correct pH and inexpensive (Handreck and Black, 2005). Water holding capacity of the media is defined as the total pore space percentage that remains filled with water after drainage has ceased. Aeration porosity is the total pore space percentage that remains filled with air after excess water has drained. Good growing media should consist of a balanced ratio between water and pore spaces. This balanced ratio is influenced by the packing of the growing medium in the seedling tray (bulk density) and its particle size. Growing media suppliers apply buffering agents to the media to correct the pH and subject the media to high air temperatures to kill pests (Handreck and Black, 2005). However, pH could also be affected by the quality of irrigation water. If pH is not monitored carefully it may cause plant water stress and may account for up to 50% yield reduction within the greenhouse (Handreck and Black, 2005).

Currently, most South African commercial forestry nurseries use mixes of predominantly composted pine bark to grow their *Eucalyptus* seedlings (SA Forestry Magazine, 2014). Pine bark has poor water holding capacity of approximately 13% and may increase up to 23% as it decomposes. However, it is characterised by high plant available water and aeration porosity. Poor water holding capacity of pine bark means it requires more frequent irrigation to reduce chances of seedling water stress (van der Westhuisen, 2009). Frequent irrigation also assist in reducing the accumulation of salt in the media

In the last 10 years, there has been a shift towards the use of coir mixed with different percentages of other growing media particularly vermiculite, perlite and pine bark (SA Forestry Magazine, 2014). Coir is a fibre that consists of a thick mesocarp or husk of the coconut fruit (*Cocos nucifera* L.). It is the by-product after the removal of valuable industrial long fibres used for ropes and mats. It consists mainly of pithy tissue particles mixed with variable proportions of short and medium length fibre. It has a bulk density ranging from 0.04 to 0.13 kg m^{-3}. However, this depends on the ratio of fibre to dust and other substrates that might be mixed with it (Evans *et al*., 1996). Coir has a high water holding capacity of close to 35% and can hold up to 700% of its dry mass in water (van der Westhuizen, 2009). Furthermore, it has high plant available water compared to other substrates. Therefore, irrigation management for coir should be different from other substrates such as pine bark. Irrigation should be in small quantities less frequently to improve the water use efficiency and reduce over-watering (van der Westhuizen, 2009). Occasional application of long irrigation intervals are commonly performed to reduce salt build up in the media.

2.3 Efficient irrigation scheduling in a nursery greenhouse

Most commercial nurseries use fixed timer-based systems to control irrigation. The major limitation for timer systems is that they do not account for daily changes in plant water use caused by daily microclimatic changes of air temperature, solar irradiance and relative humidity. The changes in plant water use caused by plant growth are also not accounted for. These limitations make efficient irrigation scheduling using timer systems difficult and inaccurate (van Iersel and Burnett, 2012). More efficient irrigation systems would potentially avoid over- and under- irrigation as may be experienced using timer-based systems.

The use of an automated measurement and control nursery irrigation system may set a new opportunity to provide nursery planting stock with irrigation water when they need it. Such automated systems are linked to sensors that periodically measure soil water content or potential. Seedlings or cuttings source water from the growing media, causing a decrease in soil water content of the media over time. The soil water sensors will detect these changes and may be used to open the irrigation valve for irrigation management when the soil water content drops below a set point (van Iersel and Burnett, 2012). The irrigation system automatically replenishes water used by plants or lost through evapotranspiration, therefore reducing the risks of plant water stress (Balendonck *et al*., 2008). Replacing the actual quantity of water lost increases the water use efficiency, reduces leaching of nutrients and water wastage (Sui *et al*., 2012). In a study by van Iersel and Burnett (2012), the soil water content of petunia was successfully controlled using dielectric sensors by keeping the growing media water content slightly above the pre-determined set point. Plants received average daily watering of 15 to 20 ml per day when they were young and watering increased to 45 ml per day per plant when they were older.

2.4 Theoretical aspects of irrigation scheduling

Irrigation scheduling is defined as a process of understanding when and how much water to irrigate (Gebregiorgis and Savage, 2006a; Annandale *et al*., 2011). Irrigation should be applied when the soil water content is still high enough to meet the atmospheric water demands without subjecting the seedling to the risk of water stress. Similarly, plants should not be over-irrigated causing excessive drainage, leaching of nutrients, poor aeration and water wastage. Therefore, understanding factors involved in timing of irrigation scheduling such as when to start, stop and the amount is important.

2.4.1 Soil water content

Gravimetric soil water content is defined as the mass of water per mass of dry soil. It is measured by heating the soil at a temperature of 105°C to evaporate water until there is no further mass loss using a thermogravimetric method (Smith and Mullins, 2000). Bound and structural water are not included in the definition of soil water content due to immobility of structural water, which is only removed at high temperature between 400 and 800°C. However, bound and structural water are in very small quantities in soil relative to free water and they are usually disregarded (Smith and Mullins, 2000).

2.4.2 Soil water potential

Soil water potential is defined as the energy required per quantity of water to transport infinitesimal amounts of water from the sample to a reference pool of pure free water at atmospheric pressure (Campbell and Campbell, 1982). Soil water potential is expressed in a state where water has no solutes, no external forces except gravity at reference pressure, temperature and elevation. Total soil water potential (ψ_T) is determined as:

$$\psi_T = \psi_g + \psi_p + \psi_o + \psi_m \tag{2.1}$$

where ψ is the potential energy per unit mass, volume or weight of water. The subscripts, g, p, o and m represent gravitational, pressure, osmotic and matric potential, respectively. In a substrate, gravitational potential (ψ_g) is the elevation of soil water in relation to the chosen reference elevation which is determined by multiplying the gravitational constant (g) by a distance to a reference point (Smith and Mullins, 2000). Pressure potential (ψ_p) is the pressure exerted by the overlaying water over the point of interest. It is calculated by multiplying g by point of measurement distance to the free water surface above it. Both gravitation and pressure potential require a ruler to measure (Campbell and Campbell, 1982). Osmotic potential (ψ_o) is defined as the decrease in the energy of water due to water mixing with solutes and may be measured by osmometer. Matric potential (ψ_m) is given by the energy per unit mass exerted by soil matrix on soil water. Matric potential is measured by tension table or equilibration methods such as filter paper method and hydraulic pressure cells (Bittelli, 2010).

2.4.3 Drained upper limit

The gravimetric drained upper limit (*DUL*, kg kg^{-1}) is the total water that the soil can hold after irrigation or rainfall once drainage has practically ceased (Gebregiorgis and Savage, 2006b; Bittelli, 2010). The duration of this stage depends on the plant water use, soil type and rate of evaportranspiration. The *DUL* water is held against gravity and may only be removed from the soil by plants, weeds or evaporation (Smith and Mullins, 2000; Annandale *et al*., 2011). Scanlon *et al*. (2007) argues that *DUL* is an imprecise term since it is not a unique value since equilibrium is never reached. Soil water may be removed by other processes in the soil such as soil evaporation and plant transpiration whilst water may be added by irrigation and dew drops. Water drainage never stops but continues at reduced rates over time (Kirkham, 2005). Soil water above the *DUL* may be taken up by plants whilst it is draining, so it is still available to plants (Ritchie, 1981). The *DUL* is influenced by organic matter content, clay type, soil texture and structure and soil temperature (Gebregiorgis and Savage, 2006b).

Richards and Weaver (1943) firstly recommended *DUL* to be -10 kPa for coarse textured soil and -33 kPa for fine textured soil if it cannot be specifically measured for a specific soil type. The *DUL* does not occur in a nursery potted media since growing media does not have the underlying soil that moves down water deep into the soil profile through capillary action. Potted media have pot capacity which is the quantity of water that stays behind the pot after irrigation and when visible drainage has stopped (Lal and Shuckla, 2004).

2.4.4 Plant available water

Plant available water (*PAW*) is defined as the quantity of water between the *DUL* or the commonly used term, field capacity (*FC*) or pot capacity and lower limit (*LL,* kg kg^{-1}) or permanent wilting point (*PWP*) (Kramer and Boyer, 1995). It is expressed as:

$$PAW = FC - PWP \quad 2.2$$

Finer textured material such as clay soil has more *PAW* compared to coarse textured material such as sand (Kramer and Boyer, 1995; Annandale *et al*., 2011). The *PAW* depends on the rate at which water is available to plant roots relative to plant water demand. Plant water demand depends on transpiration rates which may vary depending on plant size and type and surrounding environmental conditions. The supply of water to plants depends on a good rooting system with good root length density, root efficiency and soil hydraulic conductance (Kramer and Boyer, 1995). Gebregiorgis and Savage (2006b) laboratory estimated soil water content *DUL* and *LL* at 0.39 m^3 m^{-3} and 0.31 m^3 m^{-3}, respectively, for loam soil. This implied that *PAW* was 0.08 m^3 m^{-3} (8%).

2.4.5 Refill point

Refill point is the soil water level below which plant growth is measurably decreased or transpiration rates decrease by 10% from the potential value (Gear *et al*., 1977; Lukangu *et al*., 1999). At this point, plants have removed all the readily available water from large pores and start to extract from smaller finer pores with difficulty. Refill point can be estimated using Campbell and Campbell (1982) equation:

$$\theta = (\psi/a) - 1/b \qquad 2.3$$

where θ (m^3 m^{-3}) is the refill point soil water content, ψ (kPa) is the soil water potential, a = - 4 x 10^{-2} kPa and b may be calculated:

$$b = -7.82/(\ln\theta_1) \qquad 2.4$$

where θ_1 = 0.2 x silt (%) + 0.6 x clay (%) + 0.09 (Campbell and Campbell, 1982). Irrigation has been successfully scheduled using θ by Gear *et al*. (1977). Irrigation was applied when soil water content decreased below a pre-determined set point.

2.4.6 Lower limit

The *LL* is defined as the quantity of water per unit weight or per unit soil bulk volume in the soil that is tightly held by the soil that plant roots cannot absorb and may eventually wilt due to water unavailability (Hillel, 1971; Kirkman, 2005). Gebregiorgis and Savage (2006b) reported that the *LL* is the soil water content where plants are practically dead or dormant due to soil water deficit. Savage *et al.* (1996) measured the *LL* successfully using *in situ* psychrometers. The *LL* is not a fixed value in soil. It is dependent on the plant osmotic adjustment, soil texture, soil bulk density and soil stratification. If the *LL* cannot be measured, it is estimated to be -1500 kPa, however, certain plants may still absorb a very small amount of soil water held between -1500 and -6000 kPa (Kirkman, 2005).

2.4.7 Air-filled porosity

Air-filled porosity is a volume fraction of air in a porous material normally expressed as a percentage (Richard *et al*., 2008). Air filled porosity (ε_a) is calculated using:

$$\varepsilon_a = V_g/(V_g + V_w + V_s) \qquad 2.5$$

where V_g, V_w and V_s are gas, liquid and solid volumes of a substrate, respectively. Plant roots need oxygen to grow new cells, repair damaged cells and take up nutrients and water. The lack of oxygen halts the transfer of nutrients such as calcium, potassium and phosphorus (Handreck and Black, 2005). The ability of roots to absorb soil water under poor oxygen conditions is significantly reduced. Severe waterlogged conditions produce alcohol and ethylene which affects the production of plant hormones (Richard *et al*., 2008). The combination of these changes becomes visible after few days of oxygen shortage through plant morphology such as wilting, stunted growth, nutrient deficiency and drying of roots (Handreck and Black, 2005).

Some plants source their oxygen in different ways. For example, aquatic plants are capable of providing oxygen to their roots from their leaves through special-air canals in the stem (Handreck and Black, 2005). Most plants when faced with waterlogged conditions may develop this habit. However, their growth is affected than if they were able to get oxygen from the growing media. Handreck and Black (2005) reported that the frequency of irrigation in the nursery influences air filled porosity of the growing media. For example, after irrigation roots will be deficient of oxygen for a short while, but if transpiration losses are high, adequate oxygen levels will soon be available.

2.5 Practical aspects of soil water monitoring

2.5.1 Measuring soil water content

The challenge of soil water content measurement is to enable the monitoring of soil water as it diminishes within the root zone after each irrigation event. Measuring soil water content enables the irrigation manager to determine when to start and stop irrigation. The gravimetric method is the only direct method of measuring soil water content but it cannot be automated. However, soil water content may be estimated using other indirect methods that may be automated such as FDR, TDR, TDT and dual-needle heat pulse (DNHP). The detailed summary of common methods of measuring soil water content is presented in Table 2.1.

Table 2.1 Summary of techniques used to measure volumetric soil water content (θ_v).

	Gravimetric	DNHP	FDR	TDR
Automatic logging	No	Yes	Yes	Yes
Sphere of influence (mm)	Repeated sampling	50	20	100
Application	θ_v	θ_v, irrigation scheduling	θ_v, irrigation scheduling	θ_v, irrigation scheduling
Frequency	N/A	N/A	50 – 150 MHz	up to 1GHz
Examples	N/A	Model SH-1[2]	Model EC-5[2]	Model CS616-L[3]
Advantages	Simple Inexpensive	Automated Compact size	Automated Inexpensive Low power consumption Better resolution	Automated Soil specific calibration not required Insensitive to soil salinity
Disadvantages	Destructive Laborious Time consuming Not automated	Fragile Susceptible to soil temperature gradients particularly near surface	Small sphere of influence Need good soil-to-sensor contact Need soil specific calibration	Small sphere of influence Relatively expensive Specific calibration may be needed in high organic soils Need good soil-to-sensor contact

[2] Decagon Devices, Inc., Pullman, WA, USA

[3] Campbell Scientific, Inc., Logan, Utah, USA

2.5.1.1 Gravimetric method

This is the standard method of measuring soil water content that all other methods are calibrated against it (Smith and Mullins, 2000). In this method, soil samples are collected using a soil sampler such as a soil auger and then stored in airtight containers. Samples are immediately weighed in-field using a portable balance or are carried to the laboratory for weighing. Samples are then oven-dried at 105°C for 24 h. Samples are removed from the oven and cooled in desiccators and then re-weighed. The difference between wet and oven-dry mass is attributed to water loss. Soil water content can then either be expressed as gravimetric water content (g g^{-1}) or volumetric water content (m^3 m^{-3}) provided that the bulk density of the soil is known (Bittelli, 2010). Alternatively, soil water content can be estimated from the sub-samples of large soil volumes in the laboratory or in-field. Fractional gravimetric water content is expressed as:

$$\theta_g = M_w/M_s \qquad 2.6$$

where θ_g is the gravimetric water content (g g^{-1}), M_w, is the total mass of water in the sample (g) and M_s, is the total mass of dry sample (g). Volumetric water content is represented:

$$\theta_v = V_w/V_s \qquad 2.7$$

where θ_v is the volumetric water content (m^3 m^{-3}), V_w is the total volume of water that is contained by the sample, V_s is the total volume of the sample. To convert from gravimetric water content to θ_v, soil bulk density must be known and the following equation may be used:

$$\theta_v = (\rho_b\, \theta_g)/\rho_w \qquad 2.8$$

where ρ_w is the density of water and ρ_b is the bulk density of the soil.

The gravimetric method is simple and relatively inexpensive and only requires access to an oven, soil sampler and a mass balance. Disadvantages for this method are the destructive nature of sampling, time consuming, laborious work required and that the method cannot be automated (Little *et al.*, 1998; Smith and Mullins, 2000; Charlesworth, 2005).

2.5.1.2 Dual-needle heat pulse

The dual-needle heat pulse (DNHP) technique uses a heater and a soil temperature probe to determine the soil volumetric heat capacity, which can be converted to θ_v. The DNHP sensor consists of two needle probes that are parallel to each other and held at a fixed distance apart (Song *et al.*, 1998). One needle probe consists of a heater wire that produces a pulse by applying a voltage. The other needle probe houses a constantan thermocouple which senses the heat pulse. The change in heat capacity of the soil is strongly dependent on the soil water content. The sensor can then estimate soil water content changes over time by measuring warming up of soil when a heat pulse is applied. The following equation can be used to calculate θ_v (Kizito *et al.*, 2008):

$$\theta_v = [q/(e\pi r^2 \Delta T_m - (19.92x_m + 2.51)]/4.18 \qquad 2.9$$

where q (J m^{-1}) is the heat applied per unit length of the line source, e is natural logarithm base, r (m) is the distance between the heater probe and temperature probe, ΔT_m is the maximum rise in temperature of the needle (°C) and x_m is determined by dividing the soil bulk density with particle size.

The small compact size of the DNHP sensor enables it to make measurements in small soil volumes such as soil water content around a growing seed (Scanlon *et al.,* 2007). This sensor can be connected to a datalogger for automated measurements. However, probes for this sensor are very fragile and special care needs to be taken so that the distance between needle probes does not alter (Bittelli, 2010). A needle deflection of 1 mm may cause 6% error in θ_v measurements. This sensor is also susceptible to soil temperature gradients therefore precise soil temperature measurements are required for accurate measurement of θ_v (Scanlon *et al.*, 2007). Ochsner *et al.* (2003) successfully measured soyabean soil water content using DNHP probes. A comparison against the gravimetric method showed a linear relationship with an R^2 of 0.95 and 0.84 at 75 and 380 mm depth, respectively.

2.5.1.3 Dielectric permittivity sensors

These sensors use an electromagnetic technique to determine the soil water content that stems from the high permittivity of water relative to other constituents of the soil. Mineral soil, air, ice and organic matter have a dielectric permittivity of 3, 5, 1 and 1, respectively, whilst water has dielectric permittivity of 80 (Czarnomski *et al.*, 2005; Bogena *et al.*, 2007). These sensors can be connected to a datalogger for automatic soil water content measurements. Dielectric permittivity sensors are divided into three broad categories: frequent domain reflectometry (FDR), time domain reflectometry (TDR) and time domain transmission (TDT) sensors.

FDR sensors have an electronic oscillator that generates a waveform with a frequency of 50 to 150 MHz (Charlesworth, 2005; Bogena *et al*., 2007). These sensors determine the dielectric permittivity by rapidly charging and discharging a positive and ground electrode in the soil (Bogena *et al*., 2007). The measurement of a charge time *t* from the applied voltage *V* is determined using:

$$t = -RC \ln[(V - V_f + V_i)/(V_i - V_f)] \qquad 2.10$$

where R (Ω) is the series resistance, C (μF) the capacitance, V (V) the supply voltage, V_i the starting voltage and V_f the final voltage The soil dielectric permittivity can be determined by measuring the charge time *t* of the sensor when inserted in soil. Since water has a dielectrical permittivity greater than other constituents in the soil, the charge time of the soil can be correlated with soil water content (Bogena *et al*., 2007). Charging time of a capacitor depends on the dielectric permittivity and therefore when soil water content is high the capacitor will charge slowly. This means that the capacitor of a sensor embedded in wet soil will reach a given voltage threshold later compared to a capacitor in dry soil.

The advantages of FDR sensors are that they are affordable, have low power consumption and only require a simple readout device that can be left in-field to automatically measure and record soil water content (Bogena *et al*., 2007). These sensors are easy to install just by inserting them in the substrate where soil water content needs to be measured and they have resolutions greater than 0.00001 m^3 m^{-3} to changes in soil water content measurements. Disadvantages include: a small sensor sphere of influence and sensitivity to air gaps in the soil. Therefore, they need good soil-to-sensor contact for accurate measurements. Certain FDR sensor probes are sensitive to soil texture and temperature fluctuations (Bogena *et al*., 2007). Little *et al*. (1998) obtained a poor relationship between gravimetric soil water content and Thetaprobe (model ML1[4]) soil water content measurements. This was likely due to the interference caused by roots, earthworms holes and air pockets. However, Lukangu *et al.* (1999) successfully scheduled irrigation sub-hourly for cabbages using Thetaprobes (model ML1). Irrigation was applied when the soil water content dropped below the refill point.

TDR sensors determine the dielectric permittivity by measuring the time it takes for electromagnetic waves sent from the pulse generator of a cable tester to diffuse in the soil where there is a parallel pair transmission line (Topp *et al*., 1984). These electromagnetic waves are diffused through a coaxial cable to a probe inserted in a substrate. Some of these electromagnetic waves are reflected at the beginning of the probe due to impedance difference between the cable and the probe. The rest of the waves diffuse through the probe until they reach the end of the probe where they are reflected. Soil water

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[4] Delta-T Devices Inc., Cambridge, England, UK

is the main factor that alters dielectric permittivity in the soil. Dielectric permittivity can be calculated considering that the transmission velocity is known from knowing the length of the transmission line in the soil:

$$K_a = (ct/l) \qquad 2.11$$

where K_a is the soil dielectric constant, c the velocity of an electromagnetic signal in free space (i.e. speed of light) (3 x 10^8 m s^{-1}), t the travel time of the voltage pulse (s) and l the length of the soil transmission line (mm). There is a strong relationship between K_a and θ_v. Therefore θ_v can be calculated from equation given by Topp *et al.* (1980):

$$\theta_v = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} K_a - 5.5 \times 10^{-4} K_a^2 + 4.3 \times 10^{-6} K_a^3 \qquad 2.12$$

Specific soil calibration is not necessary in TDR sensors since these sensors are not affected by soil texture, salt content, bulk density and soil temperature (Topp *et al*., 1984). However, organic soils and vermiculite tend to under-estimate θ_v whilst clay loam and coarse sand over-estimate θ_v (Noborio, 2001).

TDT sensors work similarly to TDR sensors. The only difference is that TDT sensors require an electrical connection at the beginning and end of the transmission line. Therefore, the probe design for a TDT sensor is a bent metal rod so that the beginning and end of the transmission line is inserted into the sensor electronic box (Murnoz-Carpena, 2004). Advantages for these sensors are the high level of soil water content accuracy, large sensor sphere of influence, they are connected to a datalogger and are relatively inexpensive due to their simple circuitry. Disadvantages include reduced precision due to pulse distortion during transmission, soil disturbance and they need permanent installation in the soil (Murnoz-Carpena, 2004).

2.5.2 Methods for measuring soil water potential

The soil water content informs of the quantity of water in the soil. However, knowing the amount of water does not necessarily mean that this water is readily available to plants. For example, it is possible that a soil with low water content may have high *PAW* or soil with high water content may have a lower *PAW* (Lal and Shuckla, 2004). Soil water potential gives an understanding of the quantity of water that is available to plants. Measuring soil water potential depends on hydraulic equilibrium between water held in soil and the measuring device. Equilibrium can be reached through solid, liquid or vapour phase

(Bittelli, 2010). Soil water potential measuring methods are divided into laboratory and field-based. Table 2.2 summarises commonly used field-based methods of measuring soil water potential.

2.5.2.1 Pressure plate

Pressure plates are devices used to determine soil water characteristics in the laboratory. Pressure is applied to the sample allowing water to flow out through a porous ceramic plate. This constant pressure brings the sample to a specific water potential depending on the applied pressure. When the sample reaches equilibrium, its matric potential will be equivalent to the pressure applied (Bittelli and Flury, 2009). The sample is then removed from the pressure plate and oven dried to calculate its soil water content using the gravimetric method. Pressure plates work well in wet ranges between -500 and 0 kPa, but are less accurate in the dry range due to poor contact between the sample and the ceramic plate (Bohne and Savage, 1990). Determining soil water potential accurately using this method requires the sample to be in equilibrium with the ceramic cup. The only way to assume that equilibrium is reached is when there is no water flowing out of the sample. However, there are other factors that can prevent water flowing out of the sample such as: low hydraulic conductivity of the sample, shrinking of the sample and clogging of the ceramic plate (Bittelli and Flury, 2009).

2.5.2.2 Filter paper

The filter paper method is a simple and cheap method of measuring matric potential through placing filter paper in contact with the soil sample until water potential equilibration is reached (Bohne and Savage, 1990; Savage *et al*., 1992). If there is no direct contact between the sample and filter paper, equilibration occurs through the vapour phase. Once equilibration is reached, filter paper is removed and its soil water content is determined using the gravimetric method and converted to matric potential using calibration relationship curves. For the wet range, equilibration is achieved by movement of liquid water to the filter paper. Therefore proper contact between filter paper and the substrate is vital. For the drier range, equilibration is through water vapour which takes a longer time.

Table 2.2 Summary of techniques used to measure soil matric potential.

	Filter paper	Tensiometers	Electrical resistance	Heat dissipation
Measurement range (kPa)	-100000 to -1	-100 to 0	-200 to -30	-100000 to – 10
Automatic logging capability	No	Only when using a pressure transducer	Yes	Yes
Sphere of influence (mm)	100	> 100	> 100	10
Application	Matric potential	Matric potential, irrigation scheduling	Matric potential, irrigation scheduling	Matric potential, irrigation scheduling
Examples	N/A	Decagon, model TS1	Model 253-L[5]	Campbell, model 229-L
Advantages	Simple Inexpensive	Direct measurements May be automated Minimal maintenance Inexpensive	High accuracy Inexpensive Error less than 10%	Automated Wide measurement range No maintenance Insensitive to soil salinity
Disadvantages	Not automated Long equilibration time for dry range Need good contact between filter paper and soil	Limited to -100 kPa Cavitation problem Slow response time	Deteriorates over time Does not equilibrate will all soils Require temperature correction Limited to >-200 kPa	Sophisticated controller for heating is required Slow reaction time High power consumption

[5] Watermark sensors, Irrometer Co., Inc., Riverside, CA, USA

This method covers a wide water potential range between -100000 to -1 kPa (Bittelli, 2010). Filter paper, home-made temperature-equilibration box, oven, accurate mass balance, constant temperature room, filter papers and water content vs water potential relationship are all the requirements to determine soil water potential using this method (Bohne and Savage, 1990; Savage *et al*., 1992; Smith and Mullins, 2000).

2.5.2.3 Liquid equilibration method

The liquid equilibration method or tensiometer method is a direct method of measuring soil matric potential. Traditionally, due to their large size they were only used in-field, but their more recent small and compact size has enabled them to be used in small soil volumes (Smith and Mullins, 2000). Small tensiometers fitted with transducers can be used in a nursery potted media and laboratories. Tensiometers are porous ceramic cups that are connected to a pressure sensor through a tube filled with water (Bittelli, 2010). The tube allows the movement of water through the device whilst preventing air movement. When the ceramic cup is placed in soil, the pores reach water potential equilibrium with the surrounding soil. A decrease in matric potential of the soil compared to that of the tensiometer creates a water potential gradient. Water from the tensiometer is moved to the surrounding porous soil (Bittelli, 2010). Suction is detected and used to measure matric potential.

Tensiometers with transducers have precise measurements and allow connection to a datalogger or multiplexer for automated measurements (Bittelli, 2010). The limitation of a tensiometer is the formation of air bubbles in the water cavity known as cavitation (Scanlon *et al*., 2007). Cavitation is caused by a decrease in water potential. Liquid water pressure inside the tensiometer tube changes to vapour pressure causing spontaneous evaporation and air bubbles. Self-refilling tensiometer has solved this problem such as model TS1 (Decagon Devices, Inc., Pullman, WA, USA) (Charlesworth, 2005). The advantages of tensiometers are that they provide direct measurements of soil water potential, are easy to use, are commonly inexpensive, provide automated measurements using a datalogger (if fitted with tranducers) and are not affected by soil salinity. However, there are disadvantages: they may take a long time to equilibrate in soil and have a range of –100 to 0 kPa in soil matric potential measurements (Charlesworth, 2005; Bittelli, 2010). A delay in soil matric potential measurements due to poor contact between soil and sensor or hydraulic resistance of the ceramic cup has been reported by Atkins *et al*. (1998). This problem is commonly noticed in swelling clays and coarse textured soils.

2.5.2.4 Solid matrix equilibration

Solid matrix sensors consist of a porous matrix material that needs to equilibrate with the surrounding soil. These sensors measure θ_v, which is then related to soil water potential through a calibration relationship curve. There are three common solid matrix equilibration sensors that are used: electrical resistance, heat dissipation sensors and capacitance sensors.

Electrical resistance sensors consist of two electrodes embedded in a porous matrix. They are made of material that desaturates over a specific matric potential range, such as gypsum, fibreglass or gypsum wafer (Scanlon *et al*., 2007). Once the porous particles have equilibrated with the surrounding soil, water and solutes will be exchanged, meaning that the matric potential of the sensor will be similar to that of the surrounding soil (Phene *et al*., 1989). The electrical resistance of the embedded electrode decreases with an increase in soil water potential. Examples of these sensors are Watermark sensors which are made of granular material encased in polyvinyl chloride plastic, gypsum blocks and granular particles (Bittelli, 2010). Most electrical resistance sensors are sensitive to soil temperature and salinity. However, recent gypsum-based sensors slowly dissolve ions resulting in buffering capacity and hence insensitivity to salinity. These sensors come with manufacturer calibration but soil-specific calibration is often necessary for individual sensors. Advantages for these sensors are that: they allow automated measurements of soil water potential, relatively inexpensive and have a measurement error of less than 10%. Disadvantages are: sensor may deteriorates over time, the porous material does not equilibrate with all soil types, sensors require temperature correction and the dry range is limited to -200 kPa (Scanlon *et al*., 2007).

Capacitance sensors operates in the radio frequency from 10 to 150 MHz. These sensors measure the dielectric constant of soil (Scanlon *et al*., 2007). Dielectric properties are dependent on the soil water potential which is determined using calibration relationship curves. The sensor is placed in the soil so that the ceramic cup is in equilibrium with the surrounding soil. Dielectric properties can then be measured by measuring the dielectric capacity of the ceramic cup (Bittelli, 2010). These sensors require individual calibration due to different homogeneity amongst different ceramic cups. Capacitance sensors require good soil-to-sensor contact for accurate measurements. Overall advantages of these sensors are that they: can be connected to a datalogger for automated measurements, provide high soil water potential accuracy, provide soil water potential measurements over a wide range and minimal maintenance is required. Disadvantages are: sensor requires individual calibration and upper range measurements are limited by air entry to the ceramic cup (Lal and Shuckla, 2004).

Heat dissipation sensors consist of a porous ceramic cup with an embedded heating element (commonly a resistor) and a temperature sensor (commonly a thermocouple) (Bittelli, 2010). The ceramic cup is inserted in the soil so that equilibrium can be reached with the surrounding soil. The heating element is heated for a specific period and changes in soil temperature are measured. The change in ceramic cup temperature depends on the thermal conductivity which is based on the soil water content. Soil water content is then related to the soil water potential of the ceramic cup through a water retention relationship curve. These sensors are not affected by soil salinity since thermal conductivity does not significantly change with solute concentration. They measure soil water potential at a range of -100000 to -10 kPa.

Heat dissipation sensors should be calibrated individually prior to installation, otherwise the sensor output will differ from one another and limited repeatability of measurements may be experienced (Scanlon *et al*., 2007). Calibration can be done in pure water (for the *DUL*) and air (for the *LL*) to simplify the calibration process (Flint *et al*., 2002). These sensors can be used in-field, laboratory and for greenhouse studies. Advantages for these sensors are that they: offer a large range of soil water potential compared to other sensors, do not experience cavitation compared to tensiometers, can be connected to a datalogger for automated soil water potential measurement, are insensitive to soil salinity and are relatively inexpensive (Bittelli, 2010). Flint *et al*. (2002) documented disadvantages as: they require high technical skill for use, need long time to equilibrate for use in irrigation scheduling (2 min to 1 h), require individual sensor calibration and are limited to soil water potential measurements in the upper range (close to saturation).

2.6 Choosing the right sensor for automated irrigation system

Measuring the soil water content or soil water potential is fundamental for understanding water movements in the soil-plant-atmosphere continuum. Studies of water movement, plant germination and plant growth require accurate measurement of soil water. Soil water content indicates the quantity of water in the soil, whereas soil water potential is the quantity of soil water available to plants (Lal and Shuckla, 2004). Two adjacent volumes of soil at equilibrium may have significantly different soil water content. This is because water does not necessarily move from wet to dry, but rather from a high to low energy state. Soil water potential is the measure of energy status of water per unit volume (Smith and Mullins, 2000). Soil water content is most commonly used to measure crop or soil water balances where the main focus of the study is to understand soil evaporation (Lal and Shuckla, 2004). Additional measurements of matric potential are needed to understand the partitioning of soil water to evaporation, transpiration and plant use. The network of sensors to use in controlling irrigation scheduling depends on the measurement required, being either soil water content or soil water potential.

The requirements for an ideal sensor to use in irrigation scheduling with an automated irrigation system should be easy to install and maintain, rapid and precise, cost effective and allow for continuous unattended measurements (Gebregiorgis and Savage, 2006a; Sui *et al*., 2012). Balendonck *et al*. (2008) added that sensors need to enable the user to calibrate them against the gravimetric method for a specific soil type. There are a variety of sensors that have been developed and made commercially available to measure soil water content and soil water potential. Major applications for measuring and controlling soil water for irrigation scheduling were studied by many researchers (Yoder *et al*., 1997; Baumhardt *et al.*, 2000; Lukanu and Savage, 2006; Gebregiorgis and Savage, 2006a; Kizito *et al.*, 2008; van der Westhuizen, 2009). In a study by van der Westhuizen (2009), irrigation was successfully measured and controlled using capacitance soil water content sensors in potted greenhouse media. Improvements in irrigation management, yields and water use efficiency of tomatoes and cucumbers grown in a greenhouse were observed. Yoder *et al*. (1997) tested 23 soil water sensors represented in the following sensor types: capacitance, electrical resistance, neutron probe, TDR and heat dissipation to control irrigation scheduling. The capacitance sensors performed best in the study and met all the requirements for an ideal sensor. Lukanu and Savage (2006) reported that neutron scattering method meet most of the requirements for an ideal sensor. However, there are radioactive risks and the method is not automated requiring field visits. Tensiometers and heat dissipation sensors meet most of the requirements. However, they cover a limited range of soil water potential. Dielectric sensors met all the requirements and can be used for irrigation scheduling provided that the soil specific calibration is done. Similar successes in irrigation scheduling using dielectric sensors have also been reported in other studies (Chanzy *et al*., 1998; Balendonck *et al*., 2008). The sensor of choice depends on the specific measurements required, available budget and the size of container (Smith and Mullins, 2000). Cobos and Chambers (2010) recommend liquid and solid equilibration sensors for irrigation scheduling since they can be connected to an automated logging system. These sensors are also suited for applications such as greenhouse irrigation scheduling where the intention is to keep the soil at high water potential all the time and fairly accurate irrigation control is required to avoid over- and under- irrigation. Dielectric permittivity sensors work best for soil water content measurements especially if there are budget constraints (Chanzy *et al*., 1998). In situations where datalogging is not practical (or small soil volumes are involved), the use of gravimetric or filter paper method may be a useful and affordable option (Smith and Mullins, 2000).

2.7 Influence of soil properties on soil water measurements

The increase in the use of FDR and TDR sensors is due to their ease of measurements, cost effectiveness, repeatability, applicability to a range of soils and datalogging capabilities (Kizito *et al*., 2008). However, the dielectric permittivity may be influenced by factors other than soil water (Lukanu and Savage, 2006). Studies have indicated that these sensors may be affected by the soil environmental factors such as the soil temperature, electrical conductivity and salinity (Topp *et al*., 1980; Chanzy *et al*., 1998; Cobos and Campbell, 2007). The effect of soil temperature on dielectric permittivity has been reported by Topp *et al*. (1980) and Bogena (2007). The dielectric permittivity of soil water decreases by 0.36 per 1°C change in soil temperature (Bogena, 2007). Lukanu and Savage (2006) reported a soil water content error of less than 0.015 $m^3\ m^{-3}$ due to soil temperature variation between 12 and 18°C. The TDR sensor measurement is significantly affected by soils with high clay content, high organic matter content and low soil bulk density (Topp *et al*., 1980). Changes in soil bulk density and clay content for different soil layers have a small effect on the sensor and soil water content can be measured to within 0.02 $m^3\ m^{-3}$ (Lukanu and Savage, 2006). The FDR and TDR sensors may over-estimate soil water content in soils with high salt content because dielectric permittivity also depends on the electrical conductivity of the soil (Bogena, 2007).

The presence of air gaps around dielectric sensors caused by stones, earthworms channels, roots and cracks cause poor soil-to-sensor contact. Poor soil-to-sensor contact results in under-estimation of soil water measurements (Little *et al*., 1998; Kizito *et al*., 2008). Dielectric sensors under-estimate soil water content at high measuring frequencies of 150 MHz (Lal and Shuckla, 2004). Bogena (2007) argues that increasing the measurement frequency of capacitance sensors to 150 MHz may decrease sensor sensitivity to electrical conductivity and soil temperature and improve soil water content measurements.

2.8 Summary

Eucalyptus spp. play an important role in South African forestry industry for the production of pulp and cellulose. Therefore, commercial forestry nurseries are under pressure to produce sufficient *Eucalyptus* seedlings to meet the forestry industry planting demands. Most nurseries currently use fixed timer-based systems to irrigate planting stock. However, this method does not necessarily irrigate efficiently. Sustainable irrigation methods are needed such as the use of an automated irrigation system linked to a network of sensors.

To develop such a system, there are a variety of soil water measuring sensors that are commercially available. The choice of the sensor depends on the measurement interest, either soil water content or soil water potential. Commonly used sensors include: Frequent Domain Reflectometry (FDR), Time Domain Reflectometry (TDR) and tensiometers. However, each sensor has advantages and disadvantages. The ideal sensor should allow automated measurements, be inexpensive, accurate and precise, quick to measure and simple to use. The FDR sensors meet most of these requirements.

For the present study, the commercially available Decagon EC-5 soil water content sensor was used to measure and control irrigation for *Eucalyptus* planting stock. The EC-5 is a FDR sensor which appears suitable due to its low cost, reasonable accuracy and precision with the possibility of being integrated in an automated system. In addition, EC-5 allows soil-specific calibration and is able to fit inside the small volume container used for growing forestry nursery planting stock.

CHAPTER 3: LABORATORY CALIBRATION OF EC-5 SOIL WATER SENSOR IN DIFFERENT SOIL-LESS SUBSTRATES

3.1 Introduction

South African commercial forestry nurseries lose 10 to 20% of irrigation water annually due to over-irrigation of seedlings (Maree, 1992). The over- irrigation of seedlings (in seedling cavities) results in water and energy wastage, leaching of nutrients and an environment conducive to pests and diseases. This justifies the use of an automated irrigation system necessary to improve water use efficiency and enhance seedling production. The use of an advanced soil water sensor technological system may schedule irrigation based on measured soil water content and replenish water lost through root absorption and evapotranspiration. Controlling irrigation requires a frequent, inexpensive, simple to use and non-destructive method (Gebregiorgis and Savage, 2006a). The gravimetric method is a direct and accurate method for measuring soil water content. However, this method is laborious, costly, causes soil disturbance and cannot be automated (Smith and Mullins, 2000).

Indirect automated methods for monitoring soil water content and soil water potential have been researched by many authors (Chanzy *et al.*, 1998; Baumhardt *et al.*, 2000; Gebregiorgis and Savage, 2006a; Lukanu and Savage, 2006). The most common soil water content measurement methods include: dielectric sensors and dual-needle heat pulse. Of these methods, dielectric sensors, FDR and TDR are mostly used because they are inexpensive, easy to install, require a simple readout device, are precise and portable, have low power consumption and have good resolutions (Bittelli, 2010). There are many factors that may affect the accuracy of FDR and TDR sensors such as sensor calibration, installation and properties of the growing media. The FDR sensors were successfully calibrated by van der Westhuizen (2009) by wetting soil cores encased in a porous cylindrical PVC piping through capillary action until saturated. Sensors were then inserted per core to measure sensor output. Thereafter, the PVC pipes were suspended from load cells and allowed to dry through evaporation until there was no change in their mass. Soil cores were then oven dried to determine their soil water content gravimetrically. The calibration relationship between gravimetric water content and sensor output was determined. The disadvantages for this method are that there are large errors of 8.6 and 17.2% for dry and wet range, respectively, and that extended periods of saturation (14 days) and drying (41 days) are required.

The most common calibration method consists of measuring sensor output for a sensor placed in an undisturbed soil in-field or collecting the soil in-field and packing in a container in the laboratory at approximately the same bulk density as in-field. Soil samples are then collected adjacent to the sensor to determine the gravimetric soil water content. The sample volume is wetted and the procedure repeated at different soil water contents until the soil is saturated. The calibration relationship between sensor output and gravimetric water content can then be established. The disadvantages of this method are: it is laborious and time consuming when conducted in-field; soil samples collected may not represent a sensor sphere of influence and poor soil-to-sensor contact caused by air gaps may profoundly affect the measurements (Chanzy *et al.,* 1998). However, for laboratory calibration, the procedure is relatively quick and the soil sample volume for gravimetric method is representative. Morel *et al*. (2008) successfully calibrated capacitance sensor in a laboratory for a nursery growing media.

The objectives for this study were to calibrate low-cost capacitance soil water content sensors for different soil-less media against the gravimetric method and to evaluate the manufacturer's calibration against laboratory calibration equations. The laboratory calibration for the soil-less media will then be used to schedule irrigation for *Eucalyptus* seedlings in two subsequent experiments in a forestry nursery.

3.2 Materials and methods

3.2.1 Instrumentation

A CR1000 datalogger (Campbell Scientific, Logan, Utah, USA) was programmed using the ShortCut 3.0 software (Campbell Scientific) to measure soil water content at a scan interval of 5 s. A sensor standard excitation voltage of 2500 mV was used. Four commercially available EC-5 sensors (Decagon Devices, Inc., Pullman, WA, USA) were connected to the datalogger. Data were stored every 1 min by the datalogger. A high resolution mass balance (0.01 g) was used to weigh samples for determination of gravimetric water content.

3.2.2 Calibration procedure

To calibrate the sensors for different nursery media, four different substrates were used. Coir and vermiculite were sourced from Tunnel Quip (Mkondeni, South Africa) and pine bark (PB) from Organic for Africa (Greytown, South Africa). Coir/pine bark/vermiculite (CPBV) media mix (Figure 3.1) was mixed at a composition of 50% coir, 35% pine bark and 15% vermiculite at the Institute for Commercial Forestry Research laboratory (Pietermaritzburg, South Africa). A ready mixture of coir/perlite (CP) with 90% coir and 10% perlite mix composition was sourced from Sunshine Seedlings Nursery (Pietermaritzburg, South Africa). Sandy soil (Figure 3.1) was sourced from the Zululand coastal plains (Northen KwaZulu-Natal, South Africa). Each substrate was air dried and packed in a 4-L container at a bulk density of 85, 75, 42 and 1100 kg m^{-3} for CP, CPBV, PB and sandy soil, respectively. These media were packed at bulk density similar to standard nursery packing procedures. A sensor was allocated to each substrate during the calibration procedure. Sensor measurement of air dried media was taken for each substrate and a sample was collected adjacent to the sensor for each substrate using a volumetric soil sampler to determine θ_v.

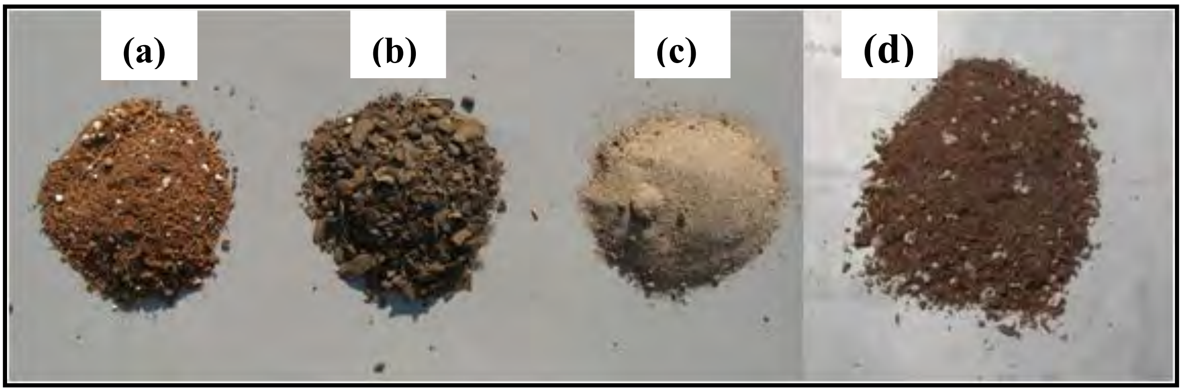

Figure 3.1 The growing media used for laboratory calibration of Decagon EC-5 soil water content sensors (a) coir/perlite (CP), (b) pine bark (PB), (c) sandy soil and (d) coir/pine bark/vermiculite (CPBV) (Photo by: Marnie Light, Institute for Commercial Forestry Research, 2014).

Thereafter, 100 ml of water was added to each substrate as evenly as possible and then mixed properly. Substrates were then re-packed to approximate original bulk density. The sensor measurement and soil sampling were done again. This process was repeated until the substrates were completely saturated. Substrate-sample were weighed using a high resolution mass balance immediately after collection. These were then placed in an oven at 105°C for 24 h. Campbell *et al.* (2006) reported that soils with high organic matter content should be oven dried at 60 to 70°C to prevent loss of volatile organics that may count as water loss. Therefore, all samples containing pine bark were oven dried at 60°C for 48 h. Samples were removed and cooled in desiccators and re-weighed. Volumetric water content was calculated by dividing the water loss in a sample by the volume of the soil sampler. The manufacturer recommends the following linear equation for EC-5 soil water content sensors to calculate volumetric water content, where θ_v represents the volumetric water content and mV is the sensor raw electrical voltage output:

$$\theta_v = 0.00211\, mV - 0.675 \qquad 3.1$$

In addition to the standard calibration procedure, as described above, a calibration procedure was also carried out using the small 0.062-L seedling plugs to understand the dynamics of taking measurements in these small volume containers. A similar method was followed.

3.2.3 Soil water potential

The soil retentivity characteristics define the relationship between soil water content and soil matric potential. These characteristics are dependent on the texture, structure, organic matter content and the bulk density of the soil.

Four samples of nursery substrates (two for CP and two for CPBV) were each packed in a core sampler at approximately the bulk density of 85 and 75 kg m^{-3} for CP and CPBV, respectively. The samples were then trimmed so that the substrate was level with the edge of the core sleeve. These were placed in a water bath and allowed to saturate by capillary action from the bottom up. After 6 h, a water vaccum was applied to the water bath to remove all trapped air in samples. The samples were then left in the water bath for 24 h to saturate. Each substrate core was weighed using a high resolution balance, within 0.01 g while water was dripping to obtain the saturated water content. The samples were then transferred to a -10 kPa pressure cell for the low matric potential range (-10 to -1 kPa). The samples were further transferred to 0.1-, 0.3-, 0.5- and finally 1- MPa pressure cell plates, respectively. The pressure was changed once the samples had reached equilibrium in each cell and then weighed before subjecting them to a different pressure. Finally, the cores were dried in an oven at an air temperature of 105°C for 24 h to completely remove any residual water. The cores were then cooled in desiccators and re-weighed to determine the water content on dry mass basis. Bulk density was determined to convert gravimetric water content (g g^{-1}) to θ_v (m^3 m^{-3}). The relationship was established using the Gardner *et al.* (1970) retentivity relationship. The retentivity relationship is expressed as:

$$\Psi = -a{\theta_v}^{-b} \qquad 3.2$$

where Ψ is the matric potential (kPa). The a and b are empirical constants that can be determined from the regression line of ln θ_v *vs* ln $|\psi|$ (Gebregiorgis and Savage, 2006a) which are given by:

$$a = \exp(a_r b) \qquad 3.3$$

$$b = -1/b_r \qquad 3.4$$

where a_r and b_r represent the linear regression intercept and slope values, respectively, for the ln θ vs ln $|\psi|$ graph.

3.2.4 Statistical tools

Regression analysis was done for each growing medium to determine the relationship between the sensor output (mV) and θ_v (m^3 m^{-3}) determined using the gravimetric method. Statistical parameters that were used are: regression co-efficient (R^2), slope, intercept, root mean square error (RMSE) and slope confidence limits at 95%. To calculate these statistical parameters, a spreadsheet developed by Savage (1998) was used for the prediction of x from a measured y. These procedures were based on Snedecor and Cochran (1980). The calibration relationship between θ_v (m^3 m^{-3}) and sensor output (mV) was used to predict θ_v from the sensor output:

$$\theta_v = ((\mathrm{mV} - a)/b)/(1 - C^2) \qquad 3.5$$

where a (mV) is the intercept, b (mV m^3 m^{-3}) is the slope of the regression line and C^2 (unitless) is calculated using the equation:

$$C^2 = ((t(0.05, n-2))^2\ SE^2)/b^2 \qquad 3.6$$

where t is the Student t statistic at 95% level of significance, n is the number of measurements and SE is the standard error of the slope determined using:

$$\mathrm{SE} = STEY(y_{1,}y_n; x_1 x_n)/(STDEVP(x_1, x_n)/\sqrt{n}) \qquad 3.7$$

where $STEYX$ is the standard error for predicted value of x from y in a regression (the root mean square error), y_1 to y_n is the range of y values in the sample of measurements and x_1 to x_n is the range of x values and $STDEVP/\sqrt{n}$ is the standard error of the x sample.

3.3 Results and discussion

3.3.1 Sensor response to soil water content

Accurate calibration procedures using field or laboratory soil may require many soil samples since soil is not homogenous (Campbell *et al*., 2009). Taking few samples might reduce the calibration accuracy due to soil physical differences influenced by soil depth, bulk density, structure and texture. However, nursery growing media are different since the mix composition and bulk density of the growing media is commonly known. Kizito *et al.* (2008) reported a high correlation between soil water content for different EC-5 soil water sensors, suggesting no need for individual sensor calibration. However, specific soil calibration using at least two sensors is recommended. Calibration equation for the two sensors, with the data pooled may be used for all other sensors (Kizito *et al*., 2008; Cobos and Chambers, 2010).

The relationship between sensor output and θ_v is presented in Figure 3.2 as the mean and standard error of data sets from three EC-5 soil water content sensors. The measurement standard error (SE) for different sensors was lower at low soil water content and increased with an increase in soil water content. The variations at high soil water content were probably due to the spatial variation in soil bulk density caused by packing differences of the growing media in the container. Differences in soil bulk density may have caused poor media to sensor contact resulting in differences in hydraulic conductivity. Small sensor output voltage variations are not unique to this calibration, as they were experienced by others (Chanzy *et al*., 1998; Campbell *et al*., 2006; van der Westhuizen, 2009), causing differences in sensor voltage.

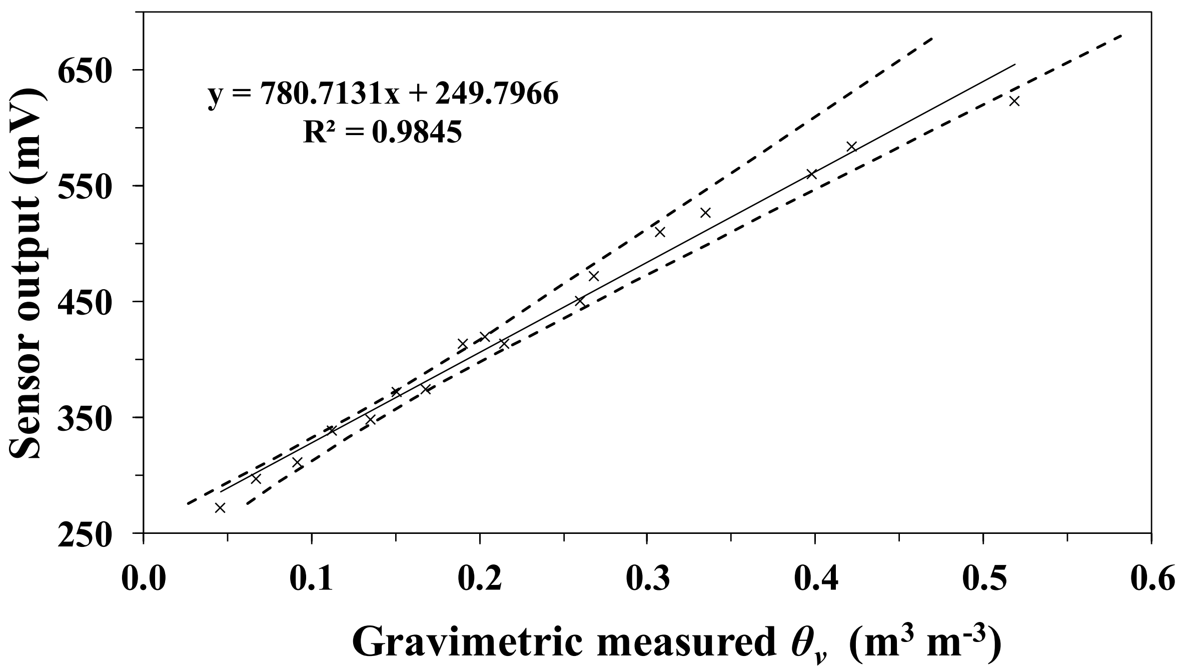

Figure 3.2 The relationship between the volumetric water content (θ_v) measured using the gravimetric method and the average sensor output (mV) for three different EC-5 soil water content sensors in a 4-L container filled with coir/perlite (CP). Error bars (I) represent standard error and dotted curves indicate the 95% prediction belts for a single predicted y-value.

EC-5 soil water content sensors are affected by the volume of soil surrounding them and small soil volumes reduces measurement accuracy (Cobos and Chambers, 2010). Cobos (2014) recommended a minimum soil volume for the EC-5 sensor to be 240 ml. In this study, however, a linear relationship was observed between θ_v measured in a 4-L container (large volume) and a 0.062-L seedling plug (small volume) (Figure 3.3). An R^2 of 0.970 indicated a good calibration relationship. However, a slope of 0.5833 and intercept of 148.53 mV was further from an ideal slope and intercept of 1 and 0, respectively. At low and high soil water content, the small container (0.062-L plugs) over- and under-estimated soil water content, respectively (Figure 3.3).

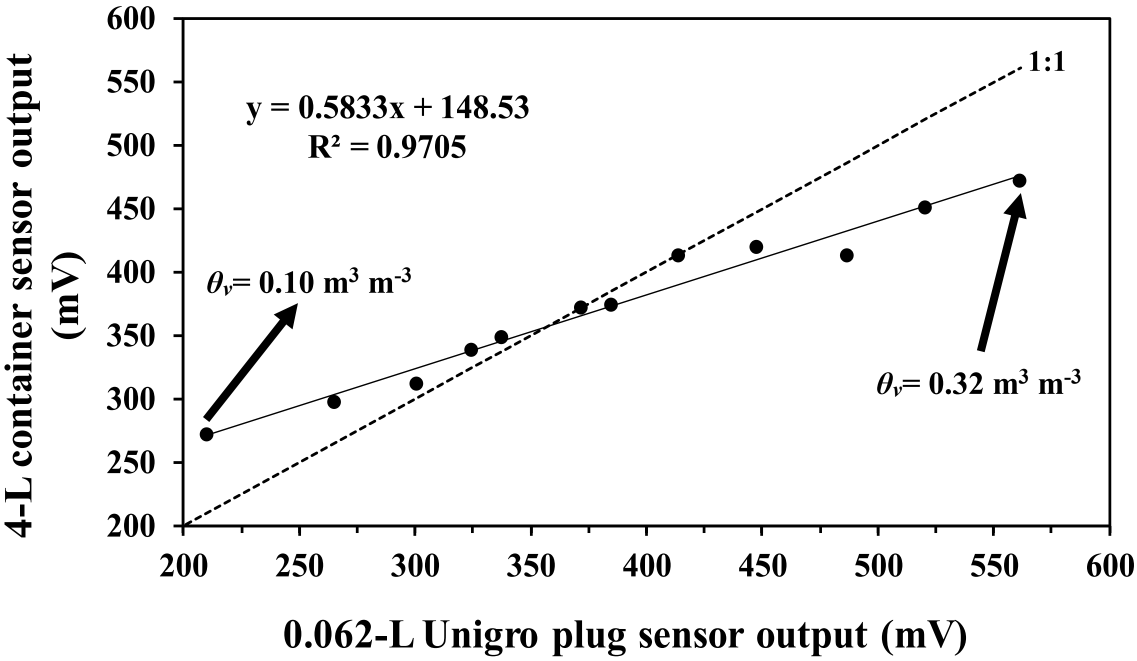

Figure 3.3 Calibration relationship for the large container (4 L) and a seedling plug (0.062 L) filled with coir/perlite (CP).

To obtain calibration relationships for the different media, the sensor output was related to θ_v that was measured using the gravimetric method for CP, CPBV, PB and sandy soil. The linear regression relationship is presented in Figures 3.4 and 3.5. The best linear relationship was obtained for CPBV followed by CP with an R^2 of 0.9963 and 0.9888, respectively, (Figure 3.4 (a) and (b)). However, the intercepts for these two substrates were greater than zero indicating a shift from an ideal intercept. The RMSE for CP was 11.73 mV compared to CPBV of 7.18 mV. The slope confidence limits for CP were slightly wider than CPBV (Table 3.1). No significant differences in intercept confidence limits were observed at both the 95 and 99% confidence limits. As a consequence, the 95% confidence belts for a predicted single y-value were wider for CP compared to CPBV (Figure 3.4 (a) and (b)).

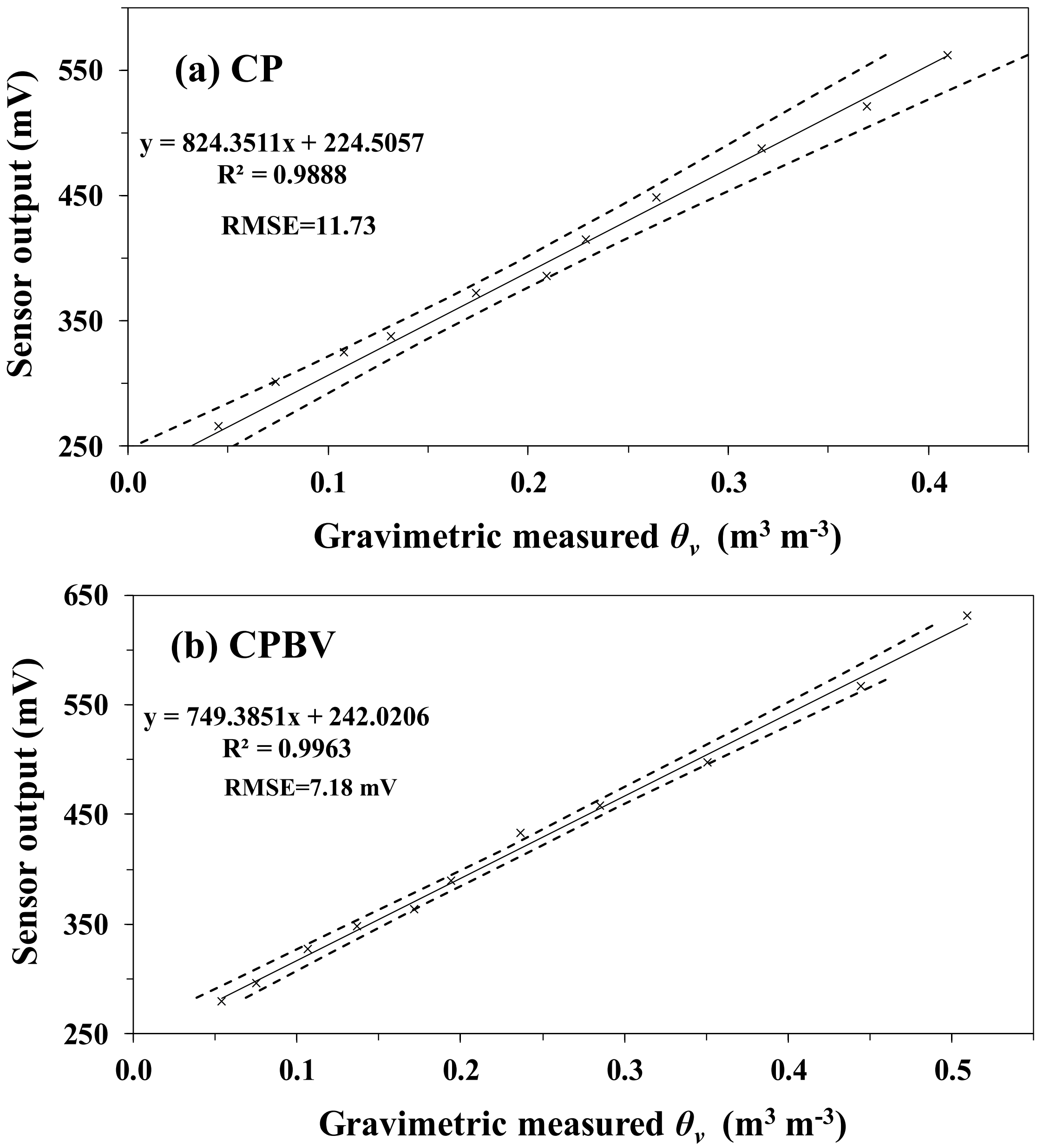

Figure 3.4 The relationship between the sensor output (mV) and volumetric water content (θ_v) determined by the gravimetric method for (a) coir/perlite (CP) and (b) coir/pine bark/vermiculite (CPBV). The dotted curves indicate the 95% prediction belts for a single predicted y-value.

An R^2 of 0.9765 and 0.9276 for PB and sandy soil, respectively, presented a good relationship (Figure 3.5 (a) and (b)). Sandy soil had the highest RMSE of 28.32 mV compared to PB of 15.14 mV. Consequently, sandy soil had the widest slope confidence limits of all the substrates at both 95 and 99% (Table 3.1). The slope and the intercept as determined for the calibration equation for CPBV was used as an offset and multiplier, respectively, for scheduling irrigation using the Decagon EC-5 soil water content sensors in the experiments that follow (see Chapter 4).

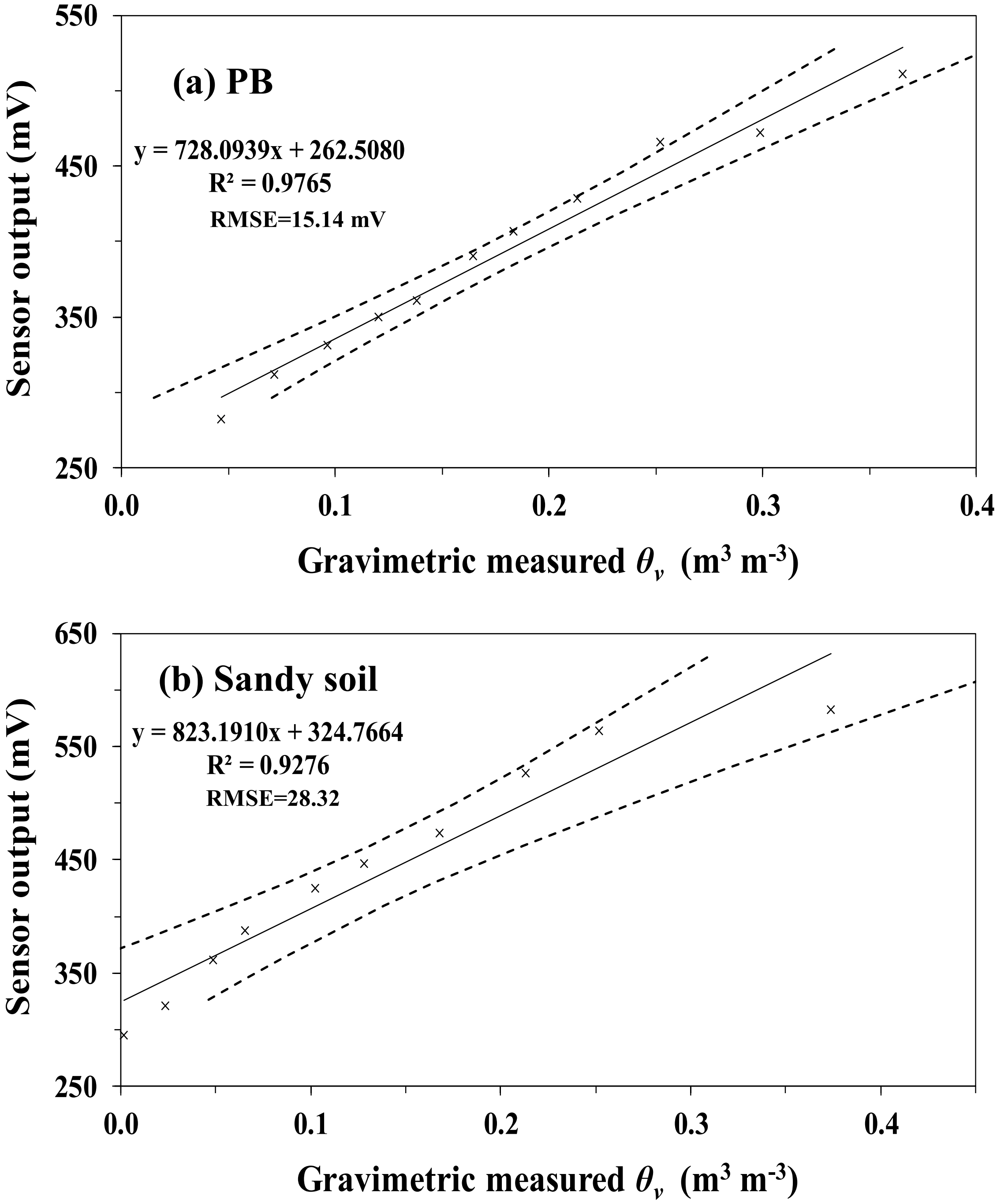

Figure 3.5 Relationship between the sensor output (mV) and volumetric water content (θ_v) (m^3 m^{-3}) determined by gravimetric method for (a) pine bark (PB) and (b) sandy soil. The dotted curves indicate the 95% prediction belts for a single predicted y-value.

Table 3.1 Statistical results for calibration of EC-5 soil water content sensor in coir/perlite (CP), coir/pine bark/vermiculite (CPBV), pine bark (PB) and sandy soil against the gravimetric method.

Statistical parameters	CP	CPBV	PB	Sand
Slope (mV m^3 m^{-3})	824.35	749.38	728.09	823.19
SE Slope (mV m^3 m^{-3})	27.74	15.14	37.67	81.32
RMSE (mV)	11.73	7.18	15.14	28.32
R2	0.98	0.99	0.97	0.92
Slope confidence limit 99% (mV m^3 m^{-3})	736.42, 912.27	700.18, 798.58	605.66, 850.52	550.33, 1096.04
Slope confidence limit 95% (mV m^3 m^{-3})	762.53, 886.16	715.13, 783.63	642.87, 813.32	635.67, 1010.70
Intercept confidence limit 99% (mV)	223.88, 225.12	241.26, 242.77	261.93, 263.08	324.3, 325.22
Intercept confidence limit 95% (mV)	224.07, 224.95	241.49, 242.54	262.10, 262.90	324.44, 325.08

3.3.2 Manufacturer calibration evaluation

The factory calibration determined using Equation 3.1 was compared to the laboratory calibration for EC-5 soil water content sensor for CP, CPBV, PB and sandy soil in Figures 3.6 to 3.9, respectively. The laboratory calibration estimates were more accurate in estimating θ_v compared to the factory calibration estimates. For CP, θ_v for dry media was 0.009 m^3 m^{-3} using the factory calibration and 0.122 m^3 m^{-3} using the laboratory calibration. The actual θ_v determined using the gravimetric method was 0.108 m^3 m^{-3} which was closer to the laboratory calibration value. At high media water content, the factory calibration estimated θ_v to be 0.510 m^3 m^{-3} compared to the laboratory calibration of 0.407 m^3 m^{-3} whilst the actual θ_v was 0.409 m^3 m^{-3}. Therefore, at low soil water content, the factory calibration under-estimated θ_v by 0.090 m^3 m^{-3} and over-estimated by 0.103 m^3 m^{-3} at high soil water content (Figure 3.6). Similar results were found by van der Westhuisen (2009) in calibrating EC-10 soil water content sensors in 100% coir where laboratory calibration estimated θ_v better that the factory calibration by 0.176 m^3 m^{-3}. According to water retention characteristic curves developed through the use of tension tables by van der Westhuizen (2009), the over- and under- estimation of soil water content does not influence the measurement of θ_v in the *PAW* range. Therefore these small differences are not significant for irrigation scheduling purposes. Both factory and laboratory calibration had an R^2 of greater than 0.98 indicating a good relationship. However, laboratory calibration had a slope of 0.989 which was very close to 1 compared to the factory calibration slope of 1.739 (Table 3.2). The intercept for laboratory calibration was very close to zero with a value of 0.002 m^3 m^{-3} compared to factory calibration of 0.201 m^3 m^{-3}.

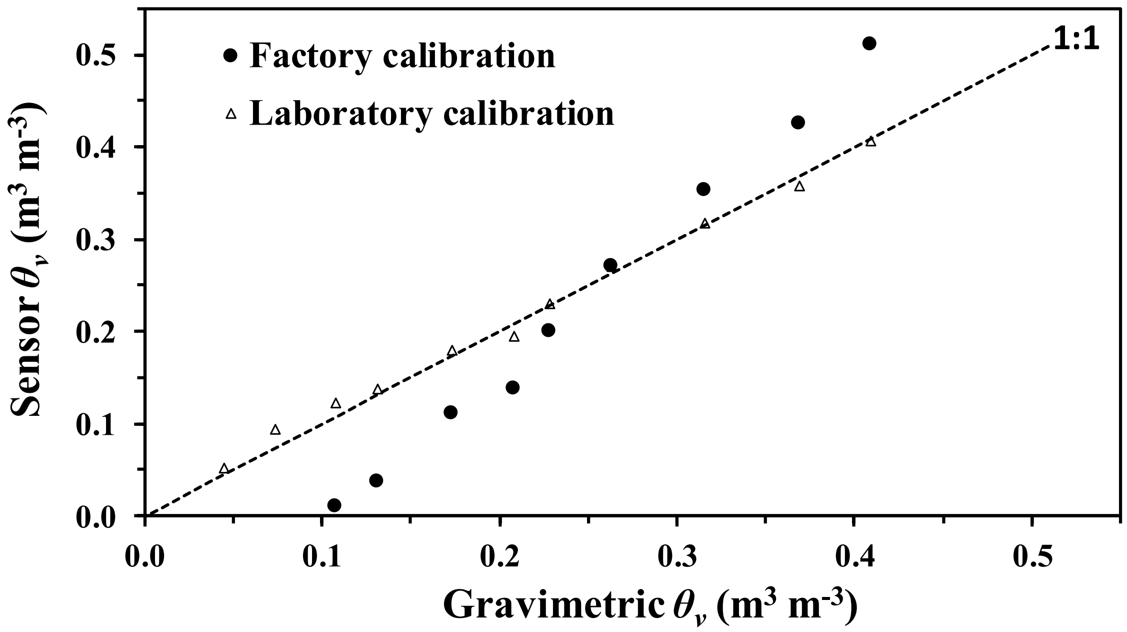

Figure 3.6 Relationship between the sensor measured volumetric water content (θ_v) and gravimetric method measured θ_v using the laboratory and factory calibrations for coir/perlite (CP).

The manufacturer specified a 5% error in soil water content measurements if a soil-specific calibration is not done (Decagon Devices, 2014). However, an error of 10 and 19% was observed for low and high θ_v, respectively. For CPBV, a linear relationship with an R^2 of 0.996 for both factory and laboratory calibration equations was found (Table 3.2). At low water content, the factory calibration under-estimated θ_v, whilst at high water content θ_v was over-estimated (Figure 3.7). The laboratory calibration had slope and intercept confidence limits of 0.974 and 0.006 m^3 m^{-3}, respectively, which were very close to an ideal slope and intercept. In contrast, the factory calibration had a slope of 1.581 and an intercept of 0.164 m^3 m^{-3} (Table 3.2). On average, the factory calibration under-estimated θ_v by 0.092 m^3 m^{-3} compared to laboratory calibration of 0.003 m^3 m^{-3} at low soil water content. At high soil water content, the factory calibration over-estimated θ_v by 0.146 m^3 m^{-3} compared to the laboratory calibration which gave an under-estimation of 0.01 m^3 m^{-3}. The statistical results in Table 3.2 justifies the importance of specific growing media calibration due to differences in soil water retention characteristics since each growing medium has different structure, texture and bulk density.

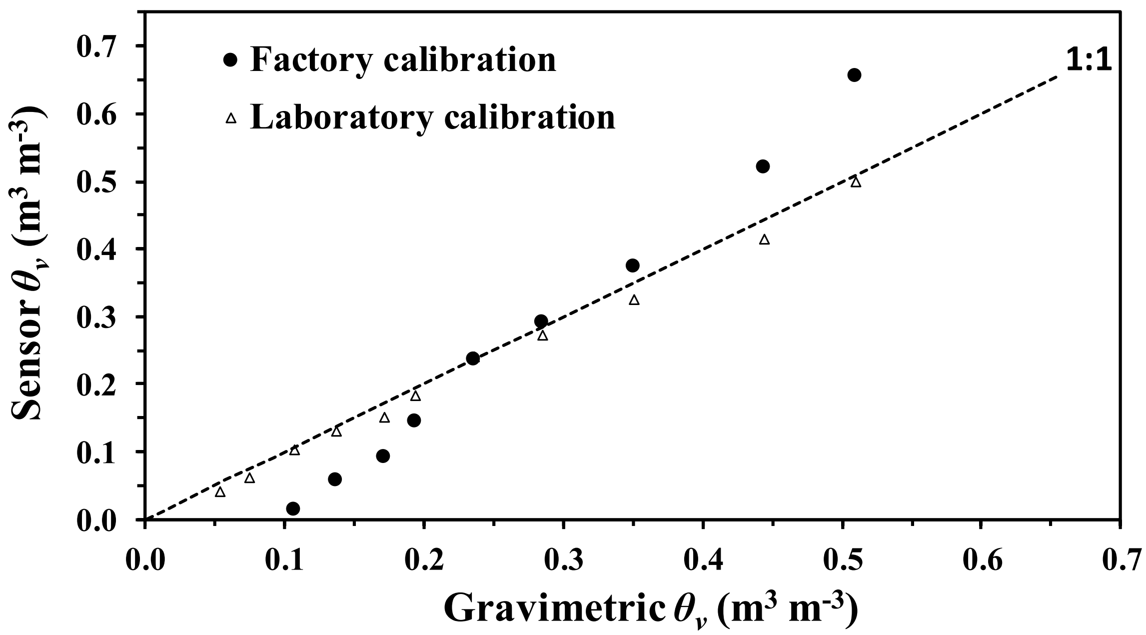

Figure 3.7 Relationship between the sensor measured volumetric water content (θ_v) and gravimetric method measured θ_v using the laboratory and factory calibrations for coir/pine bark/vermiculite (CPBV).

Table 3.2 Linear regression relationship, between factory and laboratory calibrations for coir/perlite (CP), coir/pine bark/vermiculite (CPBV), pine bark (PB) and sandy soil. Regression co-efficient (R^2) and root mean square error (RMSE) for each substrate is shown.

Substrate	Calibration type	Linear equation	R^2	RMSE (m^3 m^{-3})
CP	Factory	y = 1.739x + 0.201	0.988	0.723
CP	Laboratory	y = 0.989x + 0.002	0.988	0.016
CPBV	Factory	y = 1.581x – 0.164	0.996	0.624
CPBV	Laboratory	y = 0.974x – 0.006	0.996	0.025
PB	Factory	y = 1.536x – 0.121	0.976	0.460
PB	Laboratory	y = 0.946x – 0.006	0.976	0.029
Sandy soil	Factory	y = 2.203x + 0.030	0.988	0.131
Sandy soil	Laboratory	y = 0.939x – 0.013	0.988	0.057

Sandy soil and PB have poor water holding capacity compared to CP and CPBV due to differences in their water retention characteristics (Bohne, 2004). At very low θ_v, PB and sandy soil resulted in negative sensor output. Negative measurements were more prominent on small volume containers (0.062 L). This was most likely due to small container size creating poor media-to-sensor contact. Negative measurements were reported by van der Westhuizen (2009) in 9-L bags to be caused by air gaps in the growing media which created poor media-to-sensor contact. At low soil water content PB and sandy soil factory equation under-estimated θ_v by 0.072 m^3 m^{-3} and 0.021 m^3 m^{-3}, respectively, (Figures 3.8 and 3.9). Laboratory calibration under-estimated θ_v by 0.013 m^3 m^{-3} for PB and 0.022 m^3 m^{-3} for sandy soil. At high soil water content, the factory calibration over-estimated θ_v by 0.038 m^3 m^{-3} for PB and 0.262 m^3 m^{-3} for sandy soil whereas, laboratory calibration under-estimated PB θ_v by 0.048 m^3 m^{-3} and sandy soil by 0.032 m^3 m^{-3}.

In the study by van der Westhuizen (2009), saturation values for coir and sandy soil was estimated to be 0.910 and 0.410 m^3 m^{-3}, respectively. The *DUL* for coir was 0.607 m^3 m^{-3} and 0.270 m^3 m^{-3} for sand. The high saturation and *DUL* values for coir were due to its high porosity which is reported at 94%. In this study, the *DUL* for CP, CPBV, PB and sandy soil were estimated at 0.59, 0.51, 0.36 and 0.23 m^3 m^{-3}, respectively. This indicates that CP and CPBV media were able to hold high water content compared to other growing media.

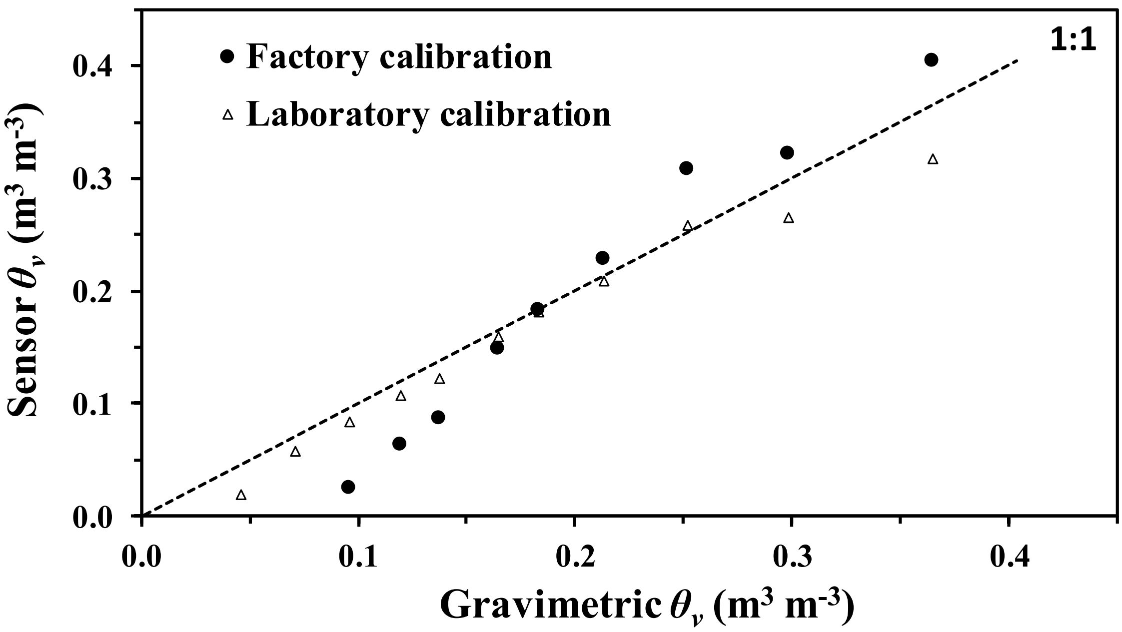

Figure 3.8 Relationship between the sensor measured volumetric water content (θ_v) and gravimetric method measured θ_v using laboratory and factory calibrations for pine bark (PB).

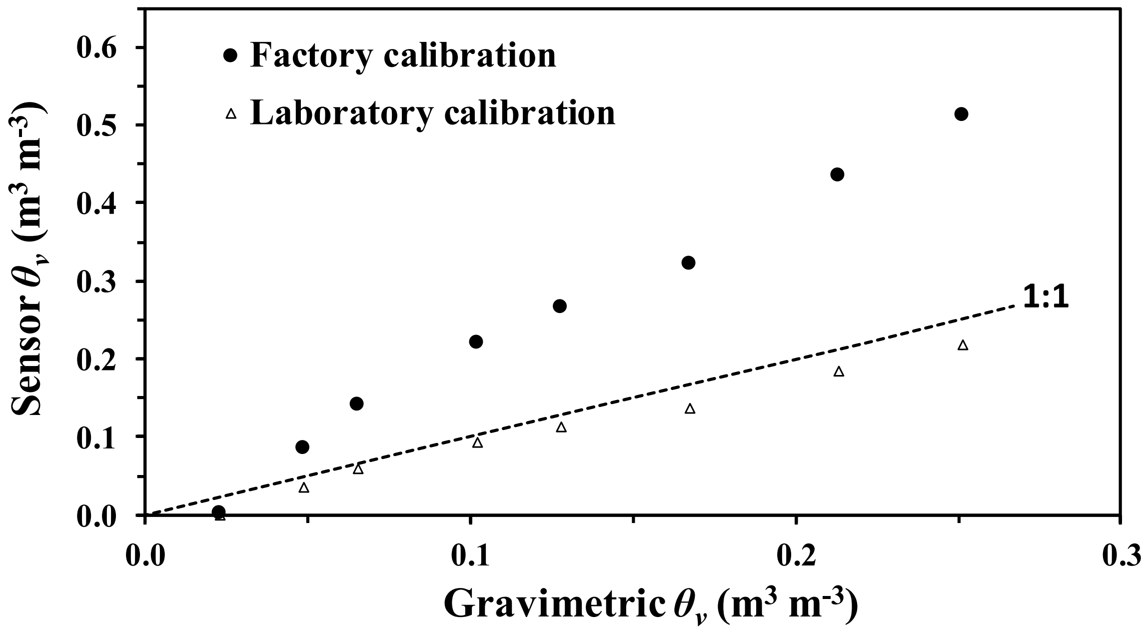

Figure 3.9 Relationship between the sensor measured volumetric water content (θ_v) and gravimetric method measured θ_v using laboratory and factory calibrations for sandy soil.

3.3.3 Soil water retention curves

From the retentivity curve (Figure 3.10), CP and CPBV water content gradually decreased with an increase in matric potential. The CP and CPBV had a saturation value of 0.67 and 0.63 m^3 m^{-3}, respectively, (Figure 3.10). At a matric potential of -10 kPa, the soil water content for CP and CPBV decreased by 0.142 and 0.28 m^3 m^{-3}, respectively. The small decrease in CP was probably due to high quantity of coir (90%). Coir holds more water and releases it slowly whereas CPBV contains pine bark which has a lower water holding capacity. Figure 3.10 indicates that at a matric potential of -1000 kPa CP and CPBV had soil water content of 0.255 m^3 m^{-3} and 0.304 m^3 m^{-3}, respectively. These laboratory-determined retention curves may be used to convert θ_v values to matric potential values should water potential be the preferred method to schedule irrigation.

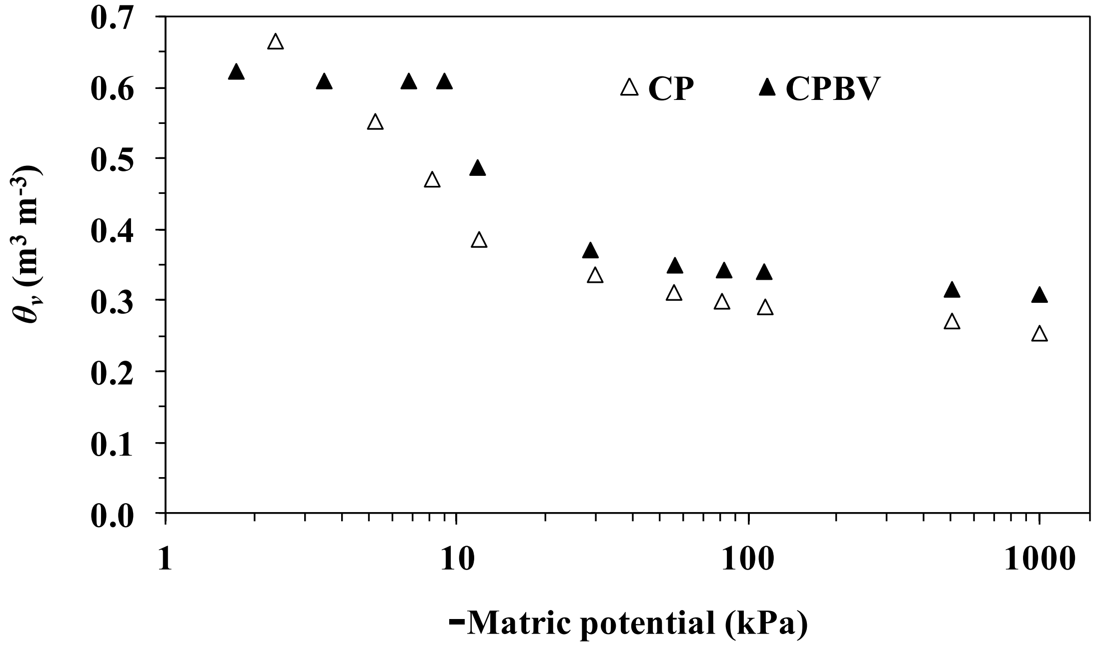

Figure 3.10 The linear-logarithmic relationship between volumetric water content (θ_v) and matric potential for coir/perlite (CP) and coir/pine bark/vermiculite (CPBV) developed through water retention curves.

3.4 Conclusions

Commercially available Decagon EC-5 soil water content sensors were laboratory calibrated against the standard gravimetric method using four different nursery growing media. Regression relationship between the sensor output and gravimetric growing media water content showed a linear relationship with an R^2 of greater than 0.92 for all growing media. Growing media water content measurements were compared in a large (4 L) and small (0.062 L) size container. Large size container over- and under-estimated growing media water content at low and high water content, respectively. Evaluation of the manufacturer calibration poorly estimated growing media water content, mostly under-estimation at low water content and over-estimating at high water content. However, over- and under-estimation did not influence the measurement of θ_v in the *PAW* range. In this study, the commercially-available Decagon EC-5 soil water content sensors were successfully calibrated to measure soil water content for seedling plugs. These calibrations proved the necessity of soil specific calibrations to increase the measurement accuracy.

CHAPTER 4: IRRIGATION SCHEDULING FOR *EUCALYPTUS* PLANTING STOCK UNDER DIFFERENT WATER REGIMES

4.1 Introduction

Most commercial forestry nurseries schedule their irrigation through timer-fixed frequencies varying with seasons and planting stock growth phase. This method works well for planting stock grown in growing media with poor water holding capacity such as composted pine bark, since it needs to be irrigated frequently with low quantities of water to prevent plant water stress (Bohne, 2004; van der Westhuizen, 2009). Most commercial nurseries are gradually changing from using pine bark medium to pure coir or coir mixed with other substrates (van der Westhuizen, 2009; SA Forestry Magazine, 2014). Therefore, timer-fixed irrigation frequencies may tend to over-irrigate coir since it has a higher water holding capacity than pine bark. Thus a more efficient method of irrigation scheduling would be useful for improved nursery management.

Phene *et al.* (1989) reported that *PAW* is not just a function of soil type, but rather an interaction between soil, plant and the atmosphere. Under greenhouse conditions where irrigation and drainage can be measured accurately using a raingauge, irrigation may be scheduled using the water balance equation (Broner, 2004). Growing media evaporation can be prevented by covering the growing media and plant transpiration can be measured by heat pulse velocity or steady stem state heat energy balance techniques. The only unknown component of the water balance equation will be the growing media water content which can be computed from the known components.

In a study by van der Westhuizen (2009), irrigation was scheduled by automatically weighing plants using load cells. Nemali and van Iersel (2006) argued that the changes in the fresh plant mass adds weight to plants which is generally neglected in the soil water content calculations. Soil water balance calculations and weighing of plants make monitoring and control of soil water content difficult. Directly, measuring soil water content using sensors may simplify the soil water content measurement and control system used.

The objectives for this study were to measure and control growing media water content of *Eucalyptus* planting stock subjected to different water regimes as regulated using capacitance sensors. Growth and development of the planting stock under different irrigation treatments will then be compared to gain an understanding of the morphological and physiological responses of *Eucalyptus* planting stock to different levels of irrigation.

4.2 Materials and methods

4.2.1 Site description

The experiment was conducted in a greenhouse at the Institute for Commercial Forestry Research (ICFR) located at the University of KwaZulu-Natal, Life Sciences Campus, South Africa (20°38´S, 30°26´E) with an altitude of 641 m (Figure 4.1). The greenhouse structure was made of corrugated polycarbonate material. The total area of the greenhouse was 36 m^2 with a north–south orientation. The greenhouse contained three seedling beds each having a solenoid valve to control overhead irrigation. Irrigation was applied using VibroNet micro sprinklers (Netafim Irrigation, Inc., Fresno, California, USA). The air temperature inside the greenhouse was fully controlled by a ducted air-conditioning unit which also assisted in controlling the relative humidity (RH). Data were automatically collected from day of year 152 – 349 (01 June to 15 December 2014) except where there was power loss, data transfer interruptions or sensor downtime.

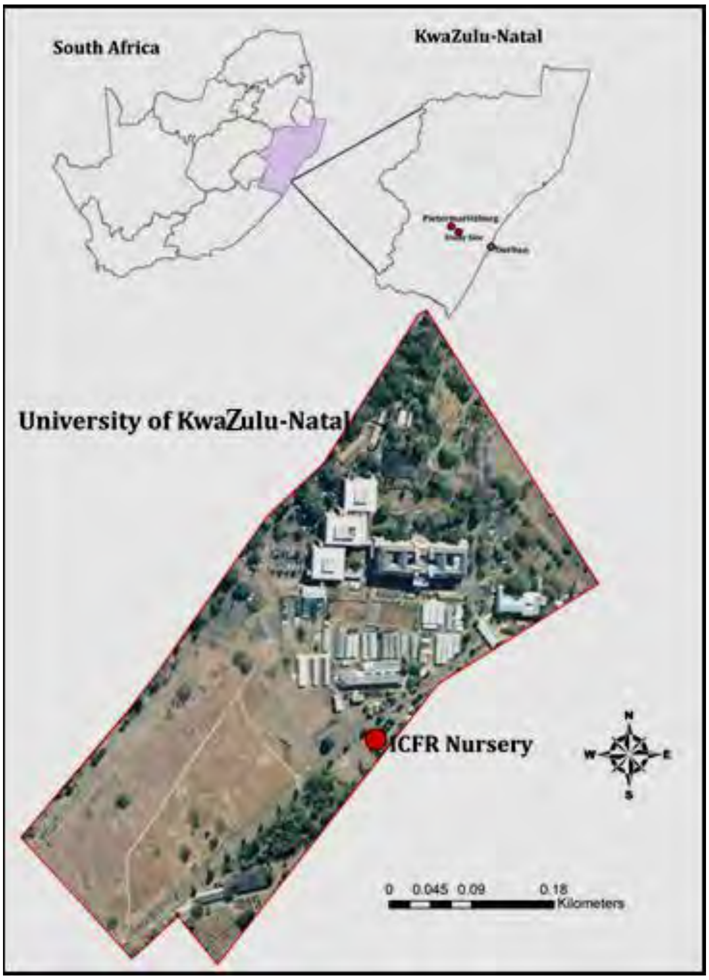

Figure 4.1 A map showing the location of the study area.

4.2.2 Description of planting stock

4.2.2.1 Experiment 1 (*E. grandis* x *E. urophylla* cuttings)

E. grandis x *E. urophylla* (GxU) is a cross breed from *E. grandis* and *E. urophylla.* This hybrid has superior wood qualities, high rooting ability and resistance to diseases. High quality raw material such as pulp and other wood products are produced by this hybrid for the commercial forestry industry (Eldridge *et al*., 1993). Trays of 45-day old GxU 111 hybrid clones were sourced from Sunshine Seedlings Nursery. These hybrid clones were vegetatively propagated into Unigro 128-cavity seedling trays using CP media at a ratio of 90:10. Commercially available Osmocote Bloom controlled released fertilizer was included in the mix to supply seedlings with fertiliser for approximately two months. Each seedling tray cavity had a capacity of 0.062 L.

4.2.2.2 Experiment 2 (*E. dunnii* seedlings)

E. dunni is a fast growing hardwood characterised by a good stem form. It is normally grown on sites susceptible to frost and where rainfall is less than required for growing *E. grandis*. Timber products from this species are of low durability but can still be used for pulp, manufacturing particle board and other solid timber end uses such as construction and flooring (Marcucci *et al*., 2003). Trays of one-month old *E. dunnii* seedlings were sourced from Sunshine Seedlings Nursery. They were grown in 128 polystyrene seedling trays in CPBV media mixed at a ratio of 50:35:15. Each seedling tray cavity had a capacity of 0.05 L.

4.2.3 Microclimate

The primary purpose of the automatic weather station inside the greenhouse was to measure the greenhouse microclimate and calculate the hourly grass reference evaporation (ETo) using ASCE method (Allen *et al*., 2006) (Figure 4.2). The sensors used are listed in Table 4.1. The CR1000 datalogger was programmed using CRBasic software (Campbell Scientific) (Appendix A) at a scan interval of 10 s. The datalogger was programmed with output tables at 2 min, hourly and daily that included the measurements shown in Table 4.2.

Table 4.1 List of variables, sensor models and their placement height in the Institute for Commercial Forestry Research greenhouse.

Variables	Units	Sensors	Measurement height (m)
Solar irradiance	$W\ m^{-2}$	EP07 Pyranometer[6]	2
Air temperature	°C	Hygroclip HC2-S3[7]	2
RH	%	Hygroclip HC2-S3[7]	2
Irrigation	mm	Campbell Scientific, TE525WS tipping bucket (three)	0.5

[6] Middleton Instruments, Inc., Hague, New York, USA
[7] Rotronic Instruments, Inc., Geelong, Melbourne, Australia

Table 4.2 The output instruction for 2 min, hourly and daily data tables.

Measurements	2 minutes and/ or hourly outputs	Daily outputs
Battery voltage	Minimum	-
Solar irradiance	Average	Total
Air temperature	Average	Maximum and Minimum
RH	Sample	Maximum and Minimum
Irrigation	Total	Total
ETo	Sample (hourly)	-

Figure 4.2 Sensors used to measure the microclimate inside the Institute for Commercial Forestry Research greenhouse (a) Middleton EP07 pyranometer and (b) Hygroclip HC2-S3 air temperature/ relative humidity (RH) sensor in a six plate Gill radiation shield.

4.2.4 Sensor description

4.2.4.1 EC-5 soil water content

The Decagon EC-5 soil water content sensor is a capacitance sensor that measures a charge stored by the soil (Figure 4.3). These sensors use the advantage of soil water having a high dielectric permittivity relative to other constituents in soil (Decagon Devices, 2014). They consist of two prongs that produce an electromagnetic field which is passed through dielectric material and then its ability to store charge is measured. The charge stored by the soil and measured by a capacitor is directly related to the dielectric permittivity of the soil or substrate. The sensor circuitry then converts the capacitor charge to a voltage so it can be measured by the datalogger. A calibration relationship between sensor output and θ_v is determined by linear regression. The sensor can be connected to the datalogger for continuous unattended *in situ* soil water content measurements. The measurement frequency of 50 MHz minimises the sensitivity of this sensor to salinity (Decagon Devices, 2014).

For this study, 12 Decagon EC-5 soil water content sensors (Decagon Devices, Inc., Pullman, WA, USA) were connected to single-ended channels of the CR1000 datalogger to measure the growing media water content in Unigro 0.062-L seedling plugs and 0.05-L polystyrene plugs for experiments 1 and 2, respectively. The excitation voltage supplied to the sensors was 2500 mV as suggested by the manufacturer. The sensors were inserted vertically into the seedling plugs with the prongs fully inserted as per manufacturer recommendation. Due to the small volume of the plug, special care was taken during insertion so that sensor prongs made good contact with the growing media and did not touch or pierce the plug wall. Sensors were inserted in cavities towards the middle of the tray to avoid edge effect.

Figure 4.3 Decagon EC-5 soil water content sensor used for measuring growing media water content in a 0.05 and 0.062 L seedling cavity.

4.2.4.2 Datalogger

A CR1000 datalogger (Campbell Scientific) was used to collect unattended *in situ* continuous measurements of growing media water content from the Decagon EC-5 sensors (Figure 4.4). The datalogger had 16 single-ended channels, twelve of these channels were used by the EC-5 soil water content sensors and two for air temperature and RH. Solar irradiance sensor was connected to differential channel. There are two pulse ports in the CR1000 datalogger: two raingauges were connected and the third raingauge was connected to the communication port which was configured as a pulse port. The other seven available communication ports were used to control the RH inside the greenhouse, control the three solenoid valves for watering at three different irrigation levels (three ports used) and for data transfer from the ICFR greenhouse to the University of KwaZulu-Natal Agrometeorology Instrumentation Mast (UKZN AIM) system (Savage *et al*., 2014).

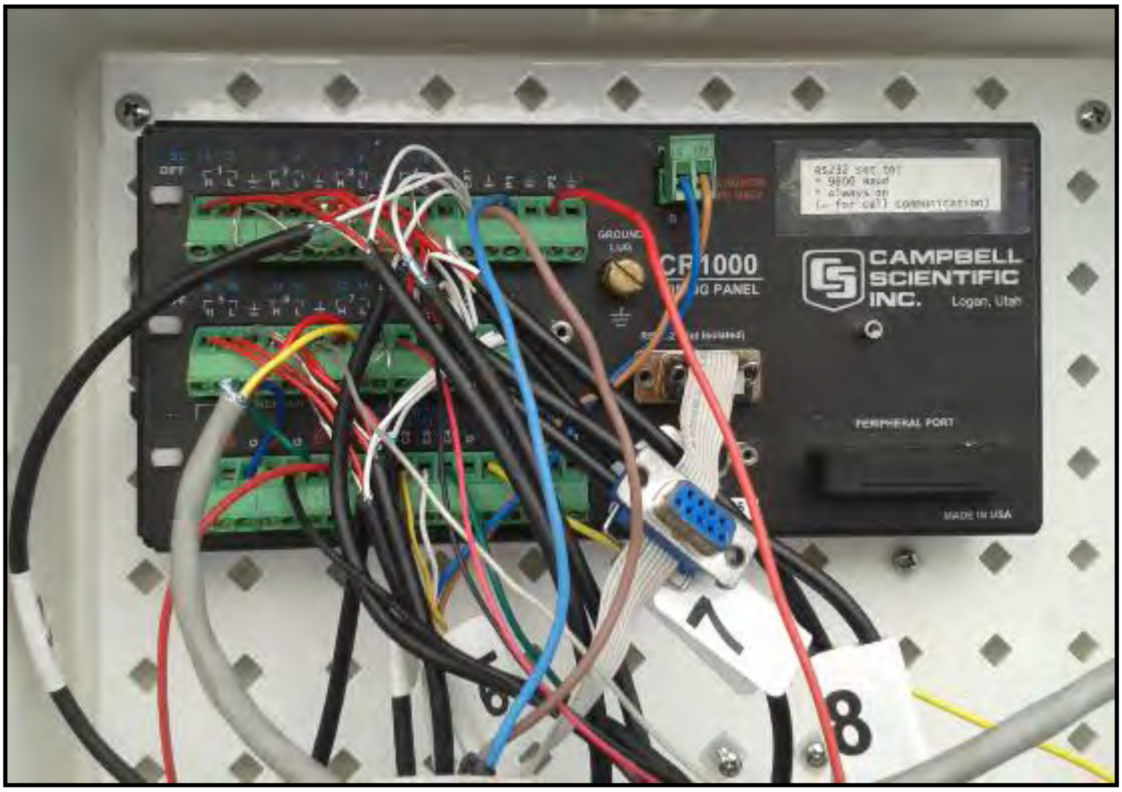

Figure 4.4 The CR1000 datalogger used to collect data and schedule irrigation at the Institute for Commercial Forestry Research greenhouse.

The datalogger was housed in a Campbell enclosure with silica gel inside the enclosure to reduce humidity. The silica gel was periodically changed when its colour changed from blue to pink. The datalogger was protected from lightning using thick logger-grounded copper cable attached to a 1 m grounded lighting rod.

4.2.5 Experimental design and treatments

For each watering treatment, three seedling trays were arranged in a row per seedling bed (Figure 4.5). Seedling beds were 1 m above the ground and overhead misters were affixed 0.5 m above the seedlings. Each seedling bed was allocated four sensors. Sensors were placed in the middle of the tray to avoid seedling edge effect for Experiment 1 and 2 (Figure 4.5). An average of four sensors per bed was used for irrigation scheduling. Before the treatments were implemented, all seedling trays were subjected to the same watering regime as commonly used for the standard South African forestry nurseries. This method consists of 6-8 fixed irrigation events of 10 min per day depending on the daily air temperature. For Experiment 1, θ_v for GxU cuttings (set in CP media) was maintained at a set point of 0.23, 0.28 and 0.36 m^3 m^{-3} for the low, medium and high watering treatment, respectively. Experiment 2 (*E. dunnii* raised in CPBV media) irrigation scheduling was set at pre-determined values of *LL* and *DUL* for each treatment. The *LL* for low, medium and high watered treatment were 0.22, 0.26 and 0.32 m^3 m^{-3}, respectively. Upper limit values were 0.26 m^3 m^{-3} for low watering, 0.32 m^3 m^{-3} for medium watering and 0.41 m^3 m^{-3} for high watering treatments. The automated irrigation system irrigated when θ_v reached a lower limit and stopped irrigation when θ_v reached the upper limit. The soil water content ranges for low, medium and high watering treatments were equivalent to a matric potential of -100 to -1000 kPa, -10 to -50 kPa and -5 to -10 kPa, respectively. Experiment 1 was from day of year 152 to 250 (1 June to 5 September 2014) and Experiment 2 day of year 250 to 349 (7 September to 20 December 2014).

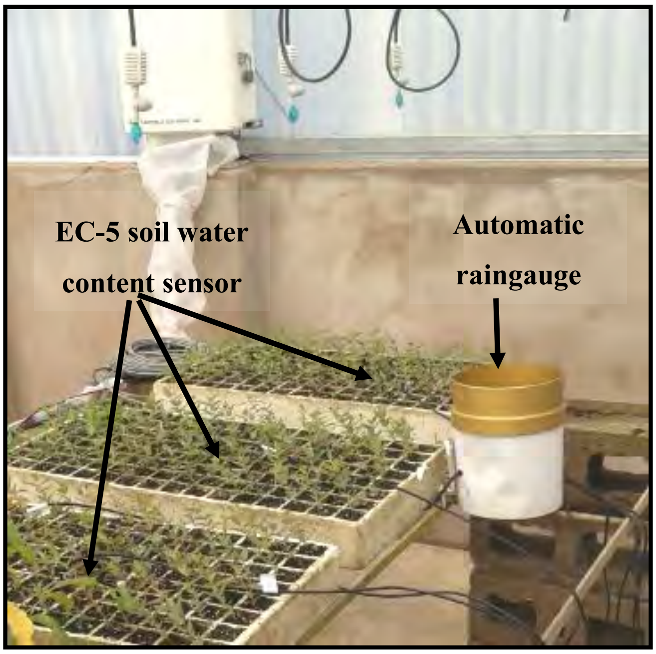

Figure 4.5 Layout of seedling trays in the Institute for Commercial Forestry Research greenhouse showing placement of the Decagon EC-5 soil water content sensors and an automatic raingauge.

4.2.6 Seedling measurements

Seedling root collar diameter (RCD) and heights were measured using a digital caliper and a ruler, respectively. For each treatment, 32 seedlings were measured per tray. Measured seedlings were selected in the middle of the tray to minimise the seedling edge. Measurements were done every second week. Seedling stomatal conductance was measured using an SC1 leaf porometer (Decagon Devices, Inc., Pullman, WA, USA) by randomly selecting 30 seedlings from the middle of the tray. Measurements were done every third week on the third fully expanded leaf of the selected seedling. At the end of the experiment, a sample of seedlings were destructively harvested to measure root and shoot length and total leaf area per treatment. Leaf area was measured using a LAI-3000 leaf area meter (LICOR, Lincoln, NE, USA). Total drainage was collected per treatment and electrical conductivity (EC) measured using a Micro CM 2202 EC meter (Crison Instruments, Barcelona, Alella, SA).

4.2.7 Web-based data communication

The ICFR greenhouse datalogger was hard-wired to the UKZN AIM system using a serial connection cable and com port of one of the dataloggers (Figure 4.6). The datalogger at the UKZN AIM system was treated as the master datalogger and the ICFR datalogger as a slave. The two dataloggers communicated through the control port where one channel acts as a transmitter (Tx) and the other channel as a receiver (Rx) with a third wire used for grounding. The ICFR datalogger was assigned to a unique proprietary address protocol (PAKBUS) with a baud rate of 38400. The connection was also assigned the following attributes: Is router, verify interval of 15 s and beacon interval of 15 s. The data transferred from the ICFR datalogger included the: two min, hourly and daily output tables. The data was then telecommunicated to the base station through a base station radio which was in turn connected to the internet server at the UKZN Agrometeorology laboratory. The data were made available on the web-based system through access using the internet or a web-enabled cellphone (http://agromet.ukzn.ac.za:5355) (Figure 4.7).

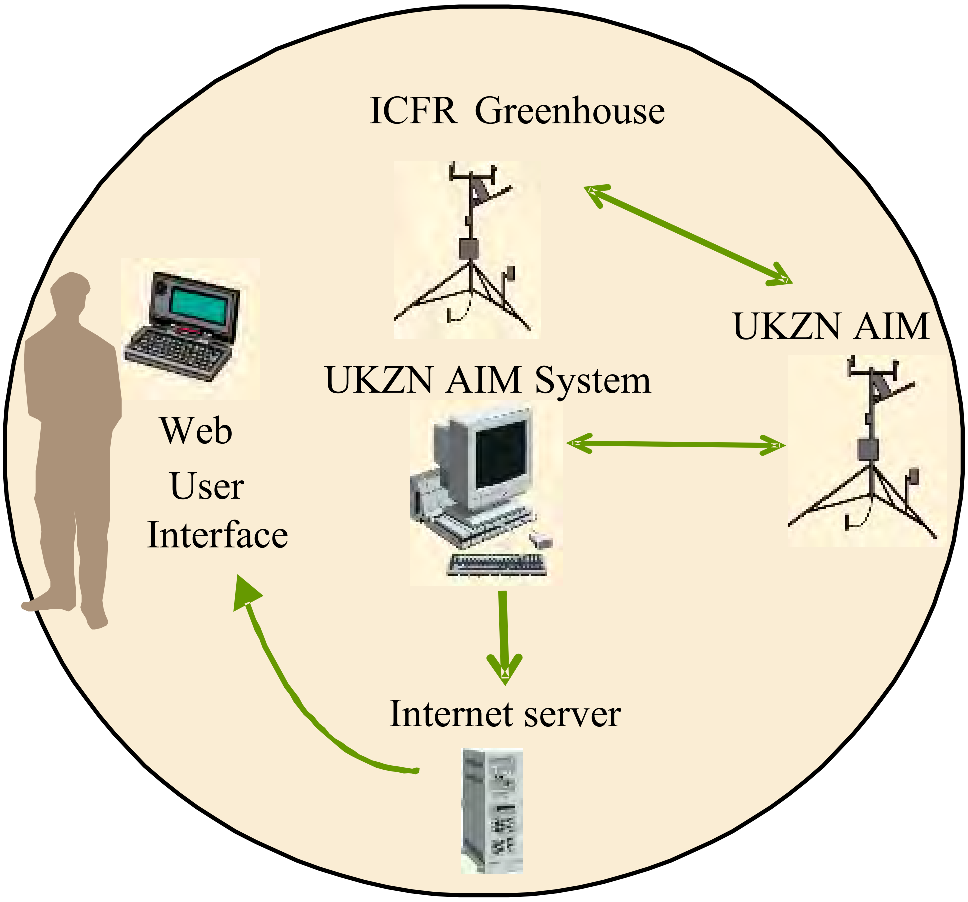

Figure 4.6 Data transfer from the CR1000 datalogger at the Institute for Commercial Forestry Research greenhouse to University of KwaZulu-Natal Agrometeorology Instrumentation Mast (UKZN AIM) system then to an internet server where users could access using an internet connection.

Near real-time ICFR greenhouse data were displayed on the specifically assigned web-screen (Figure 4.7). This screen updated the two min data tables every 10 min. Up to one week of previous data could be accessed in the form of graphs and tables – it was possible to increase this time period. The ICFR greenhouse screen showed a comparison between conditions in an open automatic weather station (AWS) and the ICFR greenhouse microclimate. Air temperature, relative humidity, solar irradiance and θ_v for the low, medium and high watering treatments were shown. The data table shown on the bottom left of the screen (Figure 4.7) could be downloaded and data extracted to Microsoft Excel for further analysis.

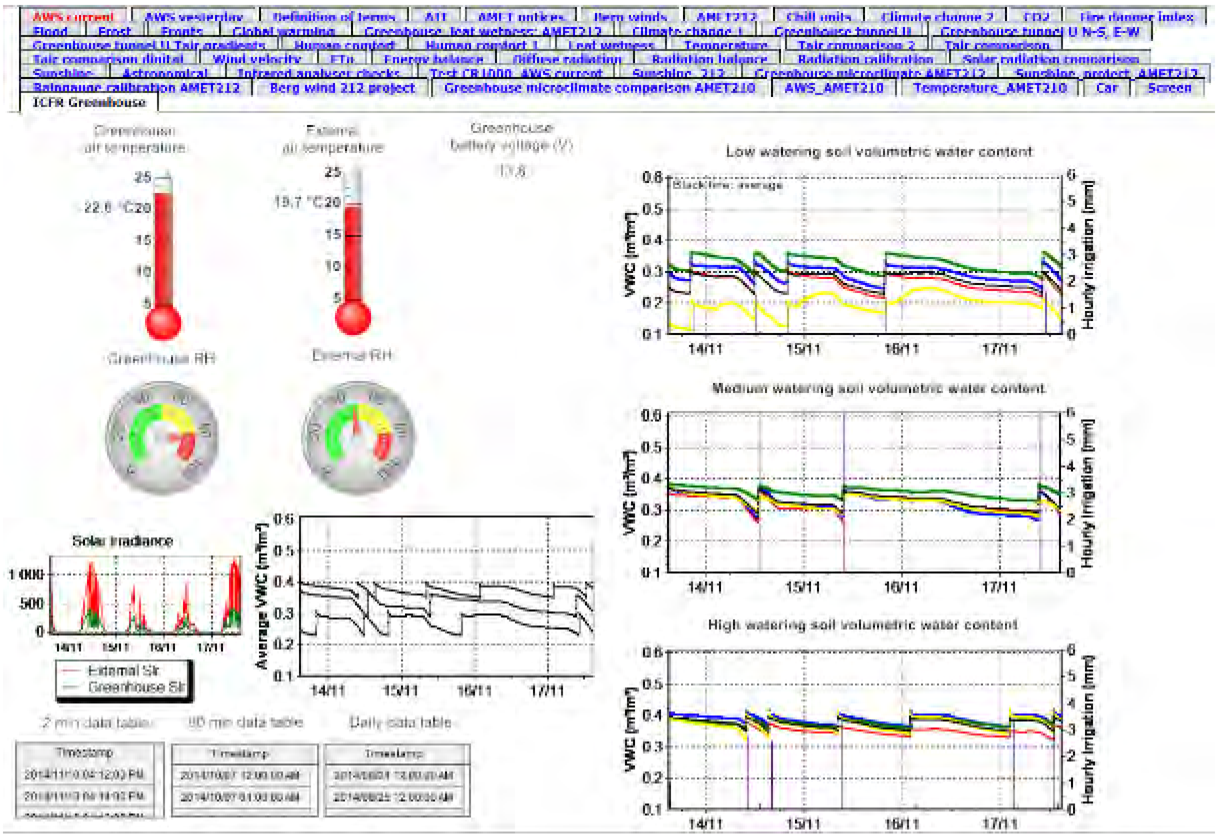

Figure 4.7 The micrometeorological conditions of the Institute for Commercial Forestry Research (ICFR) greenhouse and the soil water content measurement as displayed in near real-time by the University of KwaZulu-Natal (UKZN) web-based Agrometeorology Instrumentation Mast (AIM) system (Source: Savage, 2014a).

4.3 Results and discussion

4.3.1 Greenhouse microclimate

Solar irradiance, air temperature, RH, and wind speed are the main drivers of evaporation. Hourly grass reference evaporation (ETo) inside the greenhouse was consistently lower than the outside ETo (Figure 4.8). This was caused by reduced solar irradiance, increased RH, lower wind speed and consistently cooler air temperatures in the greenhouse. The maximum recorded hourly grass ETo between day of year 200 to 290 (2014) was 0.4 mm h^{-1} and 0.8 mm h^{-1} for the ICFR greenhouse and UKZN AIM system, respectively. For microclimatic comparison purposes, some of the data collected from the automatic weather station (AWS) inside the ICFR greenhouse and UKZN AIM system is graphically displayed in Figure 4.9. The air-conditioning unit maintained the ICFR greenhouse day-time and night-time air temperatures below 25°C and above 5°C, respectively, (Figure 4.9 (a)). For the UKZN AIM system, air temperature was fluctuating with a maximum air temperature of 36.6°C (day of year 42) and a minimum air temperature of -6.1°C (day of year 190) recorded. The RH was maintained above 60% inside the greenhouse during the day. However, at night it always reached 100% (Figure 4.9 (b)). The high RH was caused by a sealed greenhouse that did not allow the movement of outside air into the greenhouse. As a results, this high RH caused some of the seedlings to develop oedema on the leaves. The outside RH ranged from 5 to 30% during the day and 40 to 100% at night. The polycarbonate material that covered the greenhouse reduced the outside solar irradiance by at least 60%. The maximum recorded solar irradiance for the greenhouse was 300 W m^{-2} compared to outside solar irradiance of 900 W m^{-2} (Figure 4.9 (c)). The greenhouse microclimate was monitored online using the web-based system.

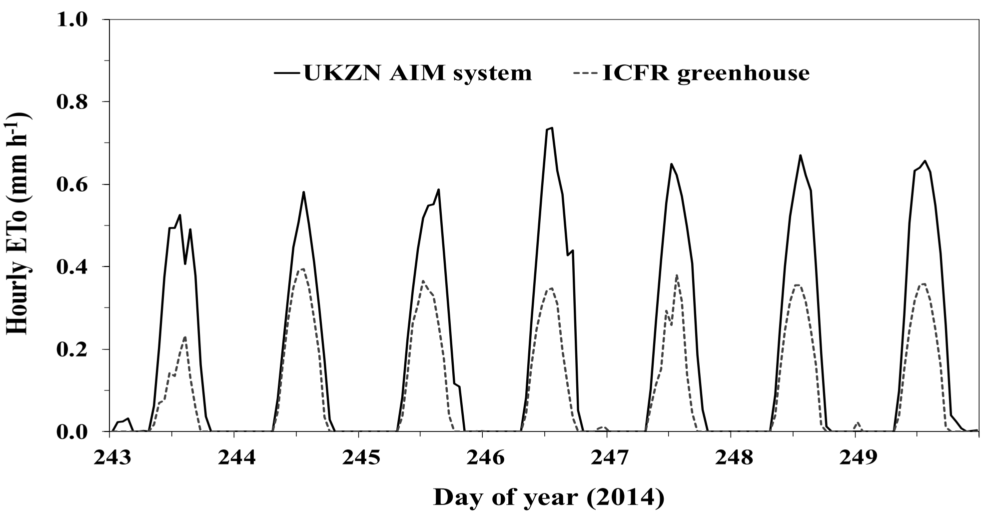

Figure 4.8 Comparison of hourly grass reference evaporation (ETo) (mm h^{-1}) for Institute for Commercial Forestry Research (ICFR) greenhouse and University of KwaZulu-Natal Agrometeorology Instumentation Mast (UKZN AIM) system for day of year 243 to 250 (2014).

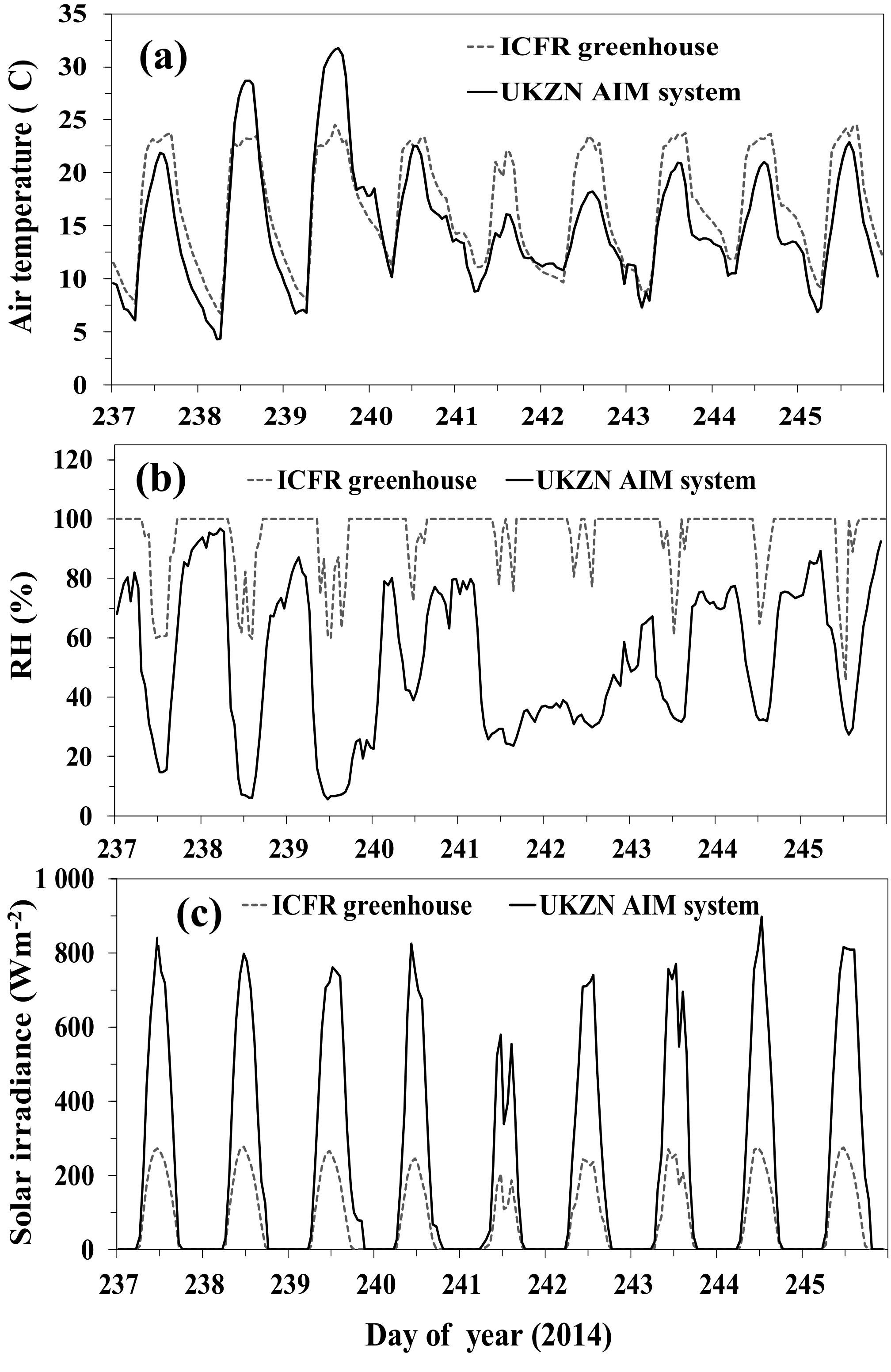

Figure 4.9 Comparison of factors that quantify microclimate for the Institute for Commercial Forestry Research (ICFR) greenhouse and University of KwaZulu-Natal Agrometeorology Instrumentation Mast (UKZN AIM) system, (a) hourly air temperature (°C), (b) hourly relative humidity (%) and (c) hourly solar irradiance (W m^{-2}) for day of year 237 to 245 (2014).

4.3.2 Sensor performance in controlling irrigation

4.3.2.1 Experiment 1 (*E. grandis* x *E. urophylla* cuttings)

The watering treatments were implemented when the *E. grandis* x *E. urophylla* (GxU) cuttings were two months old. Changes in θ_v for the low, medium and high watering treatments are shown in Figure 4.10 for day of year 241 to 244 (2014). The irrigation system was programmed to maintain θ_v for low, medium and high watering treatments greater than 0.23, 0.28 and 0.36 $m^3\ m^{-3}$, respectively. The efficiency of the irrigation system could not be tested when the GxU plants were younger due to the late implementation of the experiment. Since the irrigation system was programmed to water at pre-determined set points, too frequent short irrigation intervals were observed (Figure 4.10). The short irrigation intervals resulted in high differences in seedling plugs soil water content. Futhermore, the cuttings in the middle of the tray were over-irrigated whereas those at the edges were under-irrigated. Too frequent irrigation events especially for the high watering treatment did not allow the growing media to drain excess water, subjecting the hybrid clones to root disease risk. In this experiment, the low watering treatment applied an average of 3 mm of water per day depending on the greenhouse microclimate. Both the medium and high watering treatment applied an average of 5 mm per day throughout the growing cycle.

For all the treatments, after 2.5 months, the GxU cuttings developed a large canopy cover which blocked water from reaching the growing media. This caused some seedling plugs within a tray to be dry whereas others were wet. This problem can be observed in Figure 4.10 which shows significant differences in sensor measurements within each treatment. Figure 4.10 (b) shows the media water content in the medium watering treatment, illustrating how the plug into which sensor 8 was placed received water every time the system irrigated whereas the other three sensors received much less (or no) water. Similar effects could be observed in sensor measurements in Figure 4.10 (a) and (c). The standard deviation (SD) for the four sensors in each of the low, medium and high watering treatments were 0.0681, 0.083 and 0.100 $m^3\ m^{-3}$, respectively.

A graphical display of Figure 4.10 could be viewed on the web-based information system in near real-time. This provided an early warning to detect improper irrigation scheduling events for early intervention. For example on day of year 170, the web-based system showed that the automatic raingauge for the low watering treatment was continuously receiving irrigation. A visit to the greenhouse indicated that sensor number three in this treatment was disconnected from the seedling plug. The problem was swiftly corrected by returning the sensor to its correct position. The low watering treatment was then allowed to drain back to its *DUL*.

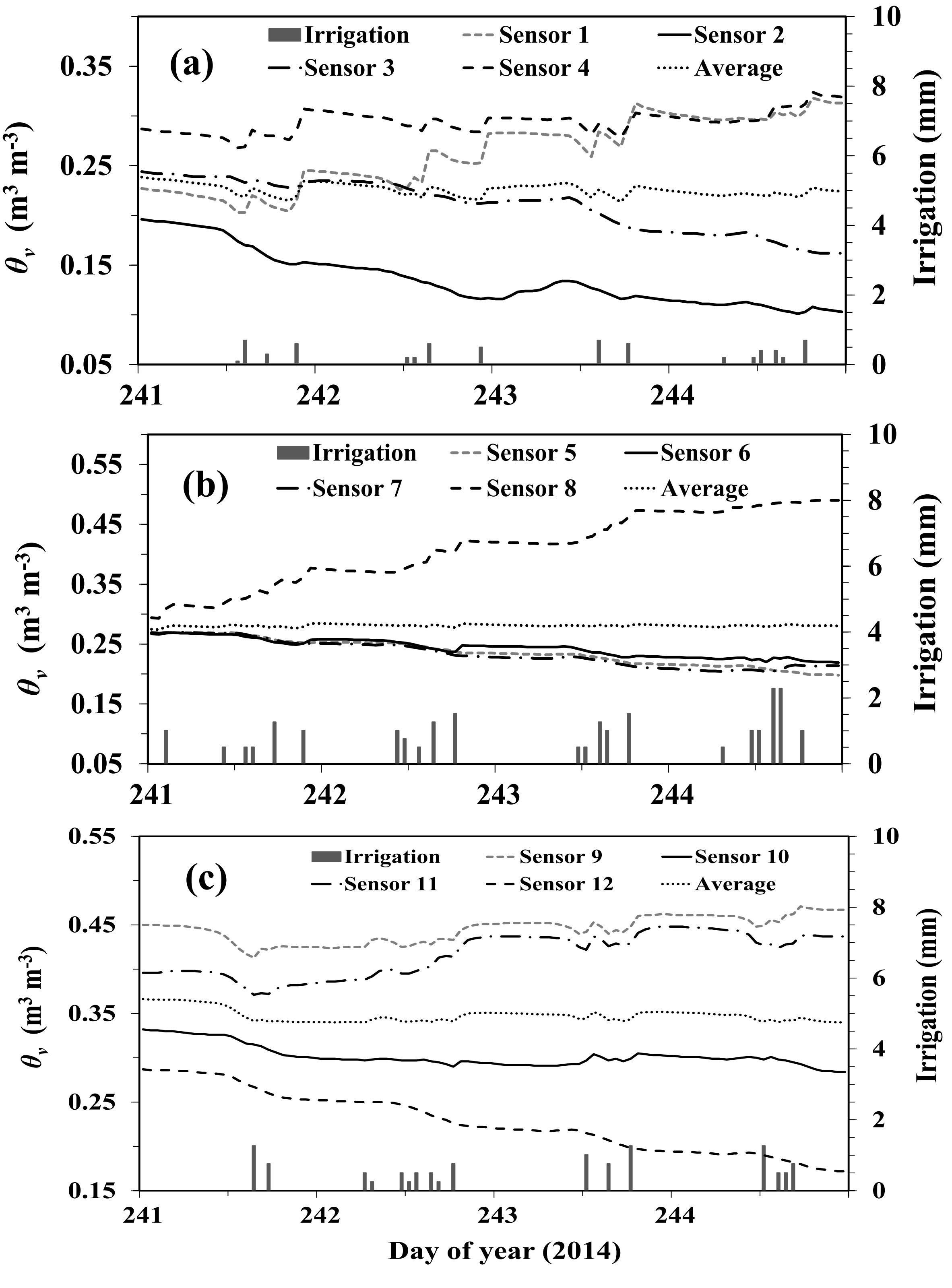

Figure 4.10 Volumetric water content (θ_v) for GxU plants at set points for treatments: (a) low ($0.23\ m^3\ m^{-3}$) (b) medium ($0.28\ m^3\ m^{-3}$), (c) high ($0.36\ m^3\ m^{-3}$) watered and total irrigation applied for day of year 241 to 244 (2014).

4.3.2.2 Experiment 2 (*E. dunnii*)

The irrigation system limitations in Experiment 1 were addressed in Experiment 2 by changing the datalogger program from irrigating using a single pre-determined set point to irrigating using θ_v set at range points with a *DUL* and *LL*. The changes in average θ_v for low, medium and high watering treatments for day of year 262 to 268 (2014) are presented in Figure 4.11. The low watering treatment was irrigated once every second day with an average of 3.5 mm when the seedlings were young. The frequency of irrigation increased with increase in seedling size and age to an average of 3 mm of irrigation per day. For the medium and high watering treatments, seedlings were irrigated daily with an average of 6.1 and 6.0 mm, respectively. The high watering treatment never dried out to the level of the medium watering treatment resulting in almost the same quantity of water applied daily to these treatments. The irrigation increased to an average of 7.13 and 8.4 mm per day after 2.5 months depending on the daily microclimate. The irrigation system automatically adjusted the increase in irrigation demands without making any adjustments to the datalogger program. For example, the low watering treatment did not water on day of year 263 and 264 (Figure 4.11 (a)). Medium watering treatment did not water on day of year 262 (Figure 4.11 (b)). This was caused by low air temperatures, high RH and low solar irradiance within the greenhouse which reduced evapotranspiration rates. The average daily drainage per treatment for the low watering treatment was 0.4 mm per 3 mm irrigation applied. For medium watering treatment, drainage was 0.68 mm per 7.13 mm of irrigation and 1.4 mm per 8.4 mm of irrigation for the high watering treatment. The soil water content standard error (SE) increased with an increase in soil water content for the low, medium and high watering treatments (Table 4.3). This can be observed in Table 4.3 where the soil water content at *LL* had a lower SE and the SE increased at the *DUL* with an increase in soil water content. This was probably caused by the change in pore space volume which affected the measurements from wet to dry media. Generally, large SE between sensor measurements was observed in the low watering treatment compared to other treatments. Chanzy *et al.* (1998) reported high SE in sensor measurements at low soil water content to be caused by perturbation in the sensor sphere of influence. The differences in sensor measurements illustrate that although the tray is watered fairly evenly, each seedling cavity is independent from others. The standard deviation (SD) between sensor measurements in the low watering treatment was 0.049 m^3 m^{-3} with an SE of 0.039 m^3 m^{-3} at the *DUL*. At the *LL*, the SD between sensor measurements was 0.0337 m^3 m^{-3} with an SE of 0.027 m^3 m^{-3}. For the medium watering treatment, the SD and SE for the *LL* was 0.020 and 0.016 m^3 m^{-3}, respectively. The *DUL* SD was 0.036 m^3 m^{-3} with an SE of 0.028 m^3 m^{-3}. The high watering treatment had the lowest sensor SD and SE of all treatments. This was most likely due to water filling the entire pore spaces within the media, improving the media-to-sensor contact. For the *DUL*, the SD was 0.022 m^3 m^{-3} with an SE of 0.017 m^3 m^{-3}. At the *LL* the SD was 0.007 m^3 m^{-3} with an SE of 0.005 m^3 m^{-3}.

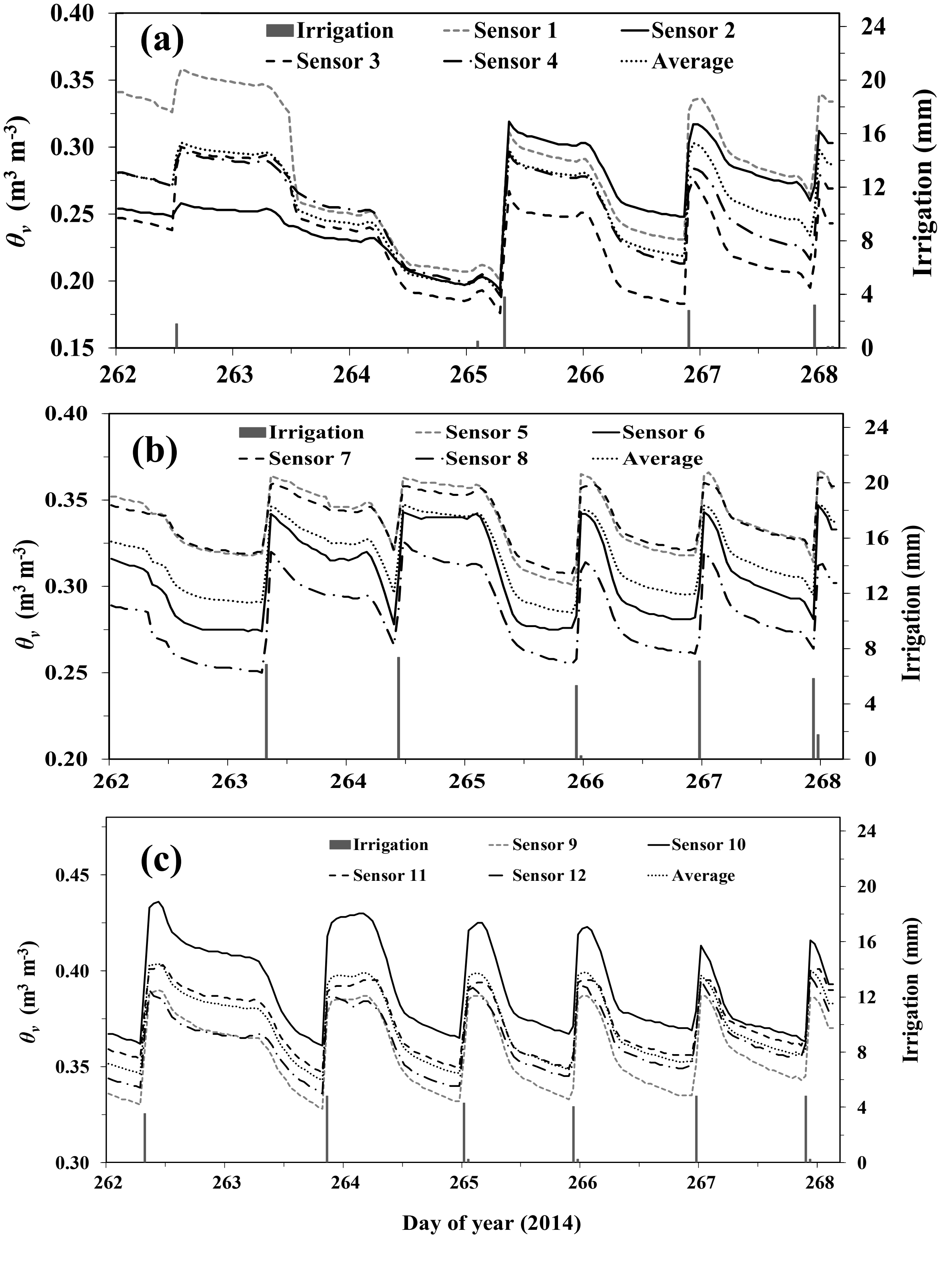

Figure 4.11 Volumetric water content (θ_v) for *Eucalyptus dunni* seedlings set at lower and drained upper irrigation limits (a) low (0.22 to 0.26 m^3 m^{-3}), medium (0.26 to 0.32 m^3 m^{-3}), high (0.32 to 0.41 m^3 m^{-3}) watered treatments and irrigation applied for day of year 262 to 268 (2014).

Table 4.3 The average volumetric water content at lower limit (*LL*) and drained upper limit (*DUL*) with standard error (SE), used for controlling irigation for *Eucalyptus dunnii* seedlings at low, medium and high watering treatments for day of year 262 to 268 (2014).

DOY	Low water				Medium water				High water			
	LL	SE	***DUL***	SE	***LL***	SE	***DUL***	SE	***LL***	SE	***DUL***	SE
262	0.27	0.031	0.30	0.041	-	-	-	-	0.35	0.012	0.40	0.017
263	-	-	-	-	0.29	0.017	0.35	0.026	-	-	-	-
264	-	-	-	-	0.29	0.016	0.35	0.020	0.34	0.011	0.40	0.016
265	0.19	0.028	0.30	0.038	-	-	-	-	0.35	0.010	0.40	0.013
266	-	-	-	-	0.28	0.019	0.34	0.029	0.35	0.009	0.40	0.018
267	0.22	0.022	0.30	0.042	0.29	0.013	0.35	0.026	0.35	0.001	0.40	0.018
268	0.23	0.027	0.30	0.048	0.30	0.012	0.35	0.029	0.36	0.007	0.40	0.019

4.3.3 Seedling growth response to different irrigation regimes

4.3.3.1 Root collar diameter and height

It was observed that the *E. dunnii* seedlings suffered from an oedema that was likely caused by consistently high RH inside the greenhouse (Figure 4.13). This generally reduced the seedling growth for all the treatments. Figure 4.14 represents RCD measurements for *E. dunnii* seedlings for day of year 262 to 331 (2014). After implementing the treatments (day of year 260) growth rates followed the treatment order low watering > high watering > medium watering (Figure 4.14) with statistical differences overlapping ($p < 0.05$). Low watering treatment experienced condition of shock with sudden reduction in irrigation water. This can be observed by decreased growth rates after day of year 270. However, seedlings were quick to adapt to the new low watering regime and used the growing media water reserves to meet their daily water requirements. Low watering treatment seedlings were visually observed to have reduced growth compared to medium and high watering treatments. At day of year 294, the high watering treatment had the highest RCD ($p < 0.05$). Differences between low and medium watering treatments were not significant at this point. This growth pattern continued to day of year 311 ($p < 0.05$). The medium watering treatment RCD tended to increase above low watering treatment at day of year 331 ($p < 0.05$).

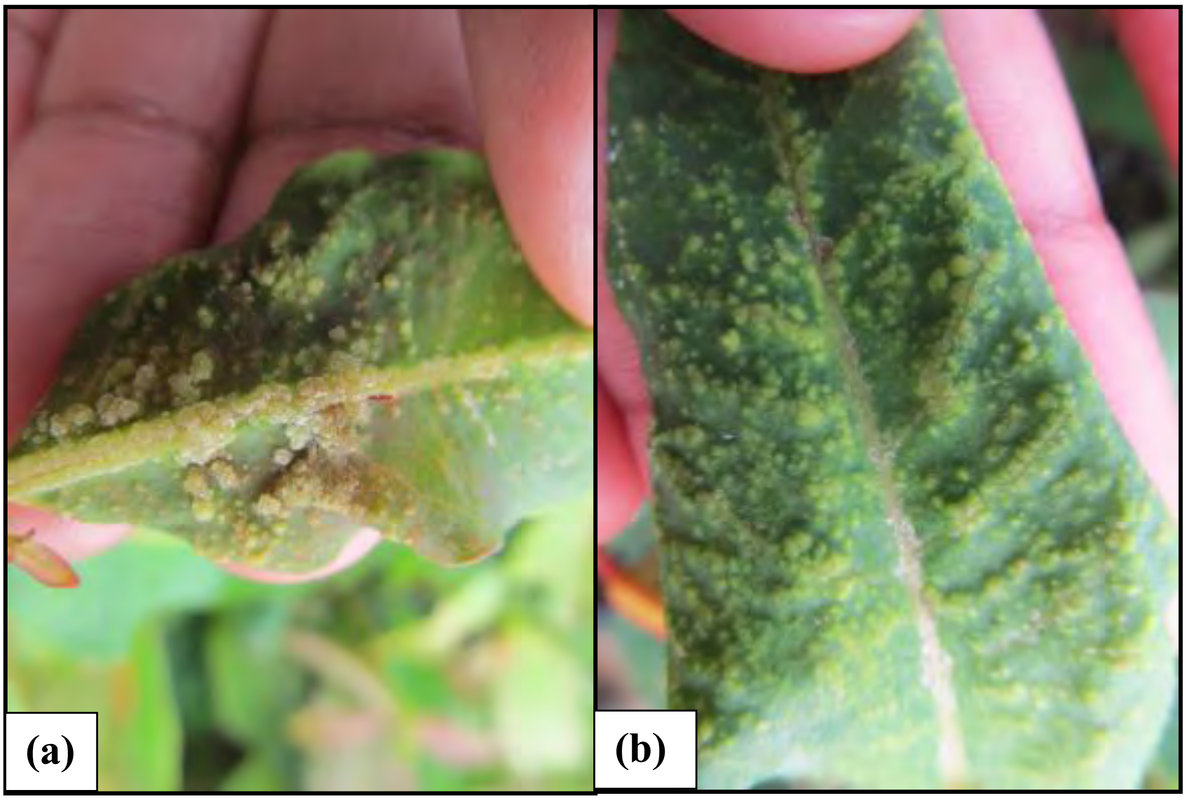

Figure 4.13 The *Eucalyptus dunnii* showing signs of oedema (a) abaxial leaf surface (b) adaxial leaf surface (Photo by Marilyn Bezuidenhout, Institute for Commercial Forestry Research, 2014).

Seedling height growth differences were not significant prior to day of year 270 (Figure 4.15). Seedling height became significantly greater in high watering treatment at day of year 280 to 331. Low and medium watering treatments had no statistically significant differences at this point. Significant differences were observed at day of year 311.

Although high watering treatment showed the highest seedling growth (RCD and heights), these seedlings were more susceptible to water deficit. For example, on day of year 276 the web-based system showed extremely low soil water content measurements on high and medium watering treatments. A visit to the greenhouse indicated that the water pump had broken. As a result plants had not been irrigated for 24 h. Seedlings in the high watering treatment were the first to show signs of water stress after 4 h followed by medium watering treatment three hours later. Intervention through manual watering was done to prevent seedlings from reaching *LL*. No signs of wilting was observed for seedlings in the low watering treatment. This indicated that these seedlings were hardier and more resistant to water stress compared to other treatments. These seedlings are more likely to survive better under harsh field conditions after transplanting. Evidence that water stressed seedlings have a potential to grow well in field has been reported by Pallardy and Rhoads (1993), Close *et al*. (2005) and Guarnaschelli *et al*. (2006).

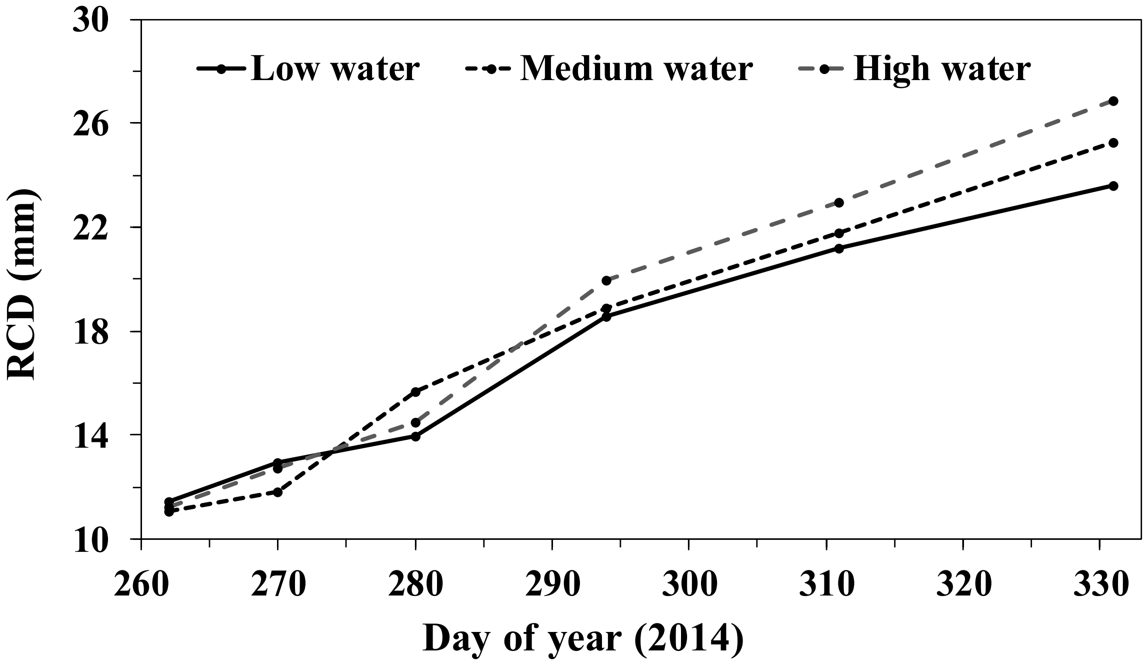

Figure 4.14 The root collar diameters (RCD) of *Eucalyptus dunnii* seedlings subjected to low, medium and high watered treatments.

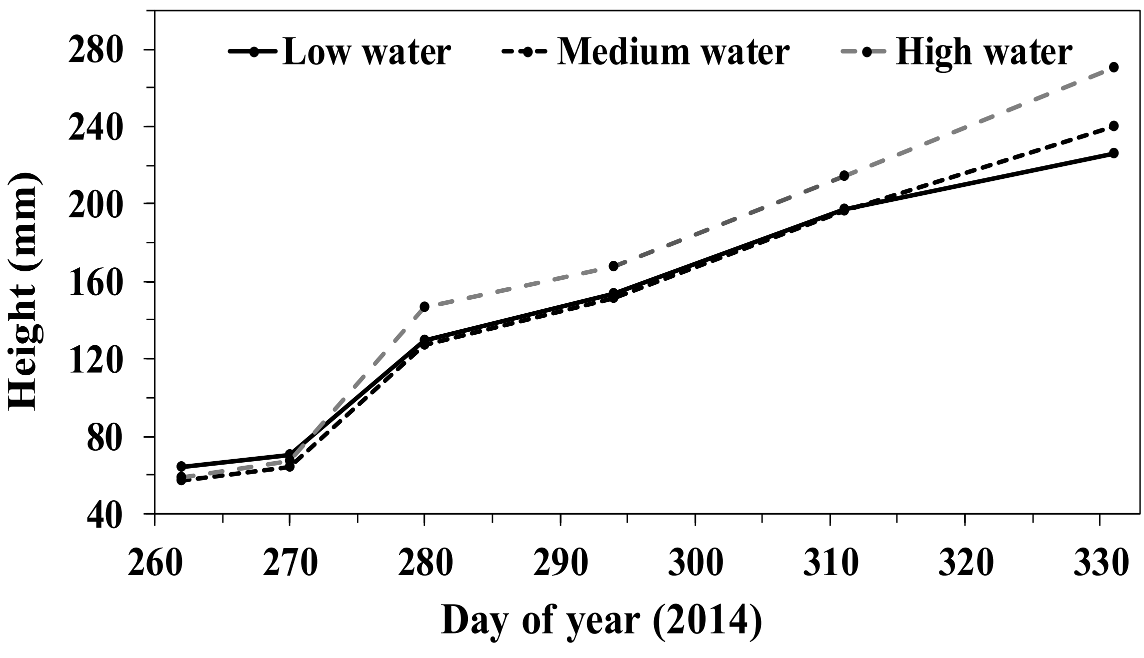

Figure 4.15 The heights of *Eucalyptus dunnii* seedlings subjected to low, medium and high watered treatments.

4.3.3.2 Stomatal conductance

It should be noted that before measuring the stomatal conductance (g_s), irrigation had to be switched off for 24 h to allow seedling foliage to dry as per SC1 leaf porometer (Decagon Devices) manufacturer's recommendations. This action probably reduced the g_s for all the treatments, although comparisons between treatments were still possible. Differences in day-time g_s for the low, medium and high watering treatments are presented in Figure 4.16 for day of year 279 to 346 (2014). After implementing the watering treatments (day of year 279), the g_s for the low watering treatment was the lowest at 55 mmol m^{-2} s^{-1} (Figure 4.16). This was most likely because the seedlings in this treatment had already significantly reduced their transpiration rates to adjust to their low watering regime. At day of year 301, g_s generally increased by 240, 210 and 270 mmol $m^{-2}s^{-1}$ for low, medium and high watering treatments, respectively. A significant decrease in g_s of 85 mmol m^{-2} s^{-1} in low watering treatment at day of year 316 was observed. Medium and high watering treatments showed an increase of 2 mmol m^{-2} s^{-1} and 186 mmol m^{-2} s^{-1}, respectively. Such temporal changes in g_s measurements could be attributed to factors such as light, CO_2 levels in the intercellular spaces, RH and air temperature, as well as the leaf water status (Jones, 1983). However, as expected, it was consistently observed that the high watering treatment had the highest g_s measurements and the low watering treatment had the lowest g_s measurement.

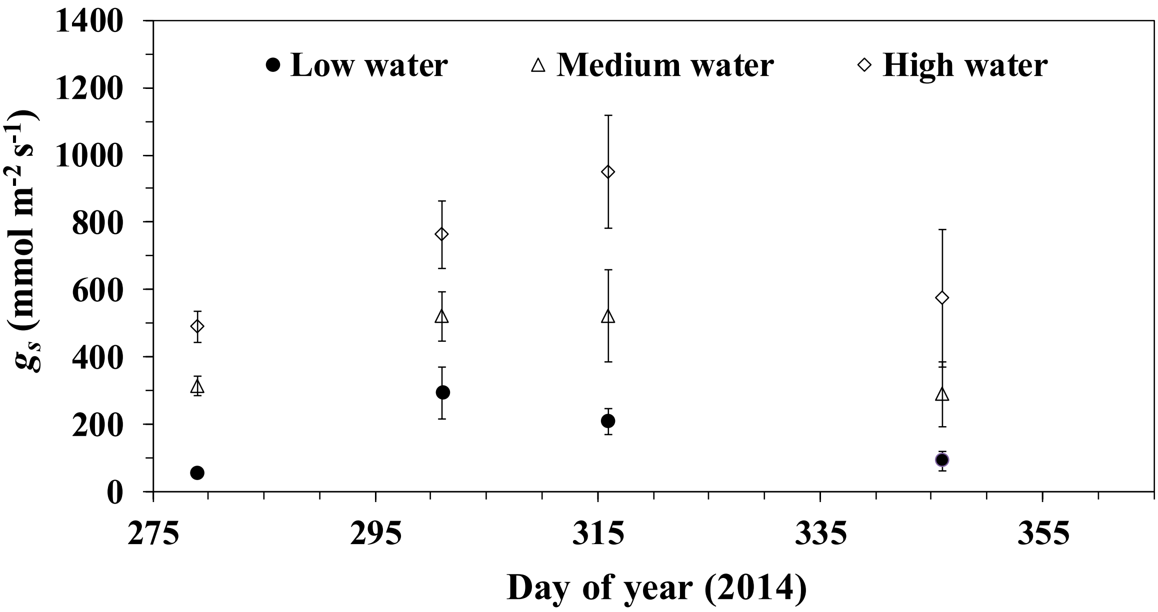

Figure 4.16 The differences in day-time stomatal conductance (g_s) for *Eucalyptus dunnii* seedlings subjected to low, medium and high watering treatments.

4.3.3.3 Seedling morphology

The root-to-shoot ratio of the seedlings from the low, medium and high watering treatments are presented in Figure 4.17. The root-to-shoot ratio for high watering treatment was 0.95, which was the closest to an ideal value of one. Medium and low watering treatment root-to-shoot ratio was 0.94 and 0.87, respectively. However, no statistically significant differences were observed between the low, medium and high watering treatments ($p > 0.05$). The slightly lower root-to-shoot ratio in the low watering treatment was probably caused by lower levels of water not allowing for sufficient root growth of seedlings in this treatment. On the other hand, the seedlings in the high watering treatment had greater shoot mass, balanced by sufficient root growth. This is also indicated by the high seedling leaf area in this treatment (Figure 4.18). Root volume in the high watering treatment had to be high enough to absorb enough water to meet the high seedling foliage transpiration demands. Leaf area of seedlings in the medium watering treatment was 20% lower than the high watering treatment and the low watering treatment had the lowest leaf area (30% less than the high watering).

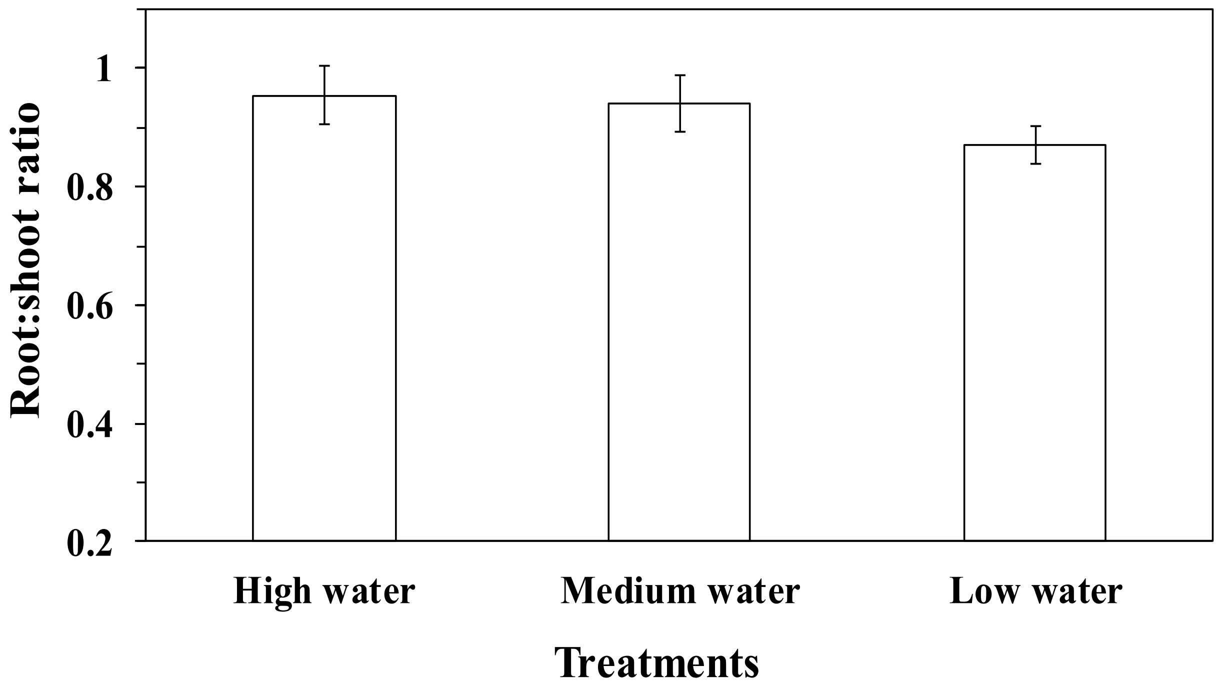

Figure 4.17 Comparison between root-to-shoot ratio for *Eucalyptus dunnii* seedlings at the end of the growing phase for low, medium and high watering treatments. Error bars (I) represent standard error.

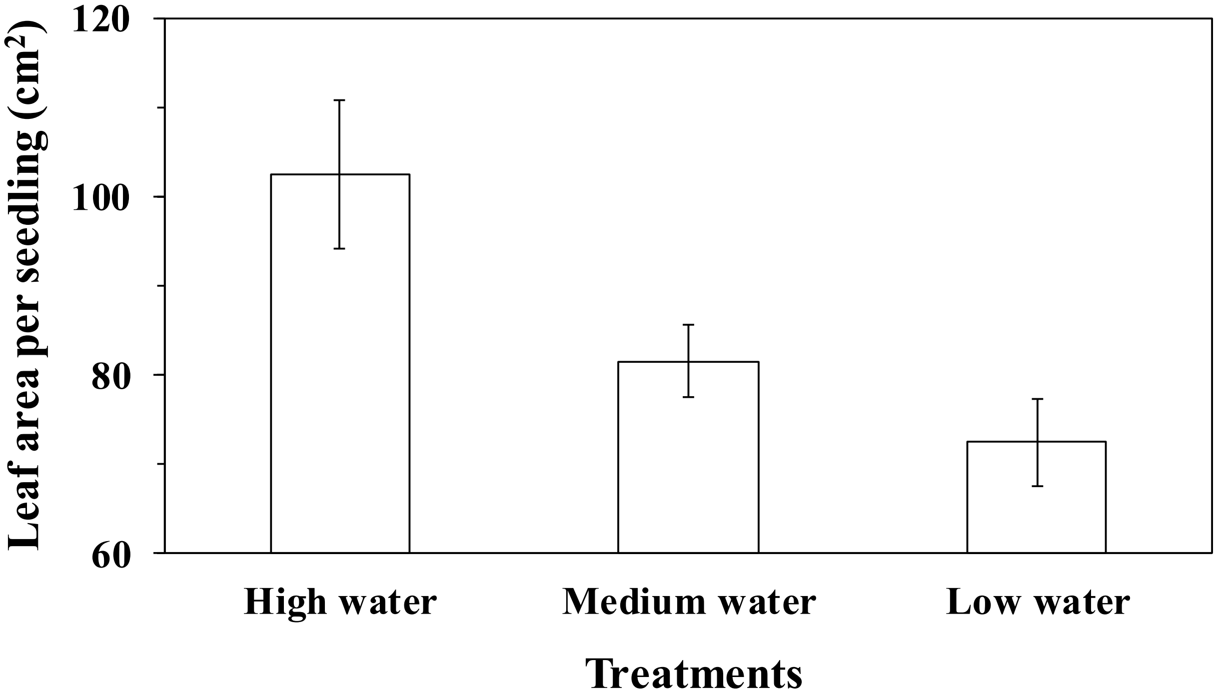

Figure 4.18 Leaf area per seedling for *Eucalyptus dunnii* seedlings at the end of the growing phase for low, medium and high watering treatments. Error bars (I) represent standard error.

4.3.3.4 Electrical conductivity

Electrical conductivity (EC) measurements for drainage collected two months after the implementation of the watering treatments are shown in Figure 4.19 for day of year 299 to 340 (2014). The low watering treatment had the highest EC of 175.6 µS/cm[8] at day of year 299 compared to medium and high watering treatments with 117 µS/cm and 76.7 µS/cm, respectively. The irrigation water EC was 70 µS/cm. The higher EC in the low watering treatment was likely due to less drainage which allowed for improved retention of nutrients in the growing media. A gradual decrease in EC was observed across all the treatments. However, the medium watering treatment showed the fastest decrease in EC of 29 µS/cm between the day year 299 and 340 compared to a decrease of 12.4 µS/cm and 9.7 µS/cm for the high and low watering treatments, respectively. The high watering treatment had the lowest EC of all treatments almost equivalent to irrigation water. This implies that high irrigation may have caused a reduction in the nutrient content of the growing media.

[8] None standard SI units are used, as is common practise 1µS/cm = 0.1 µS/mm

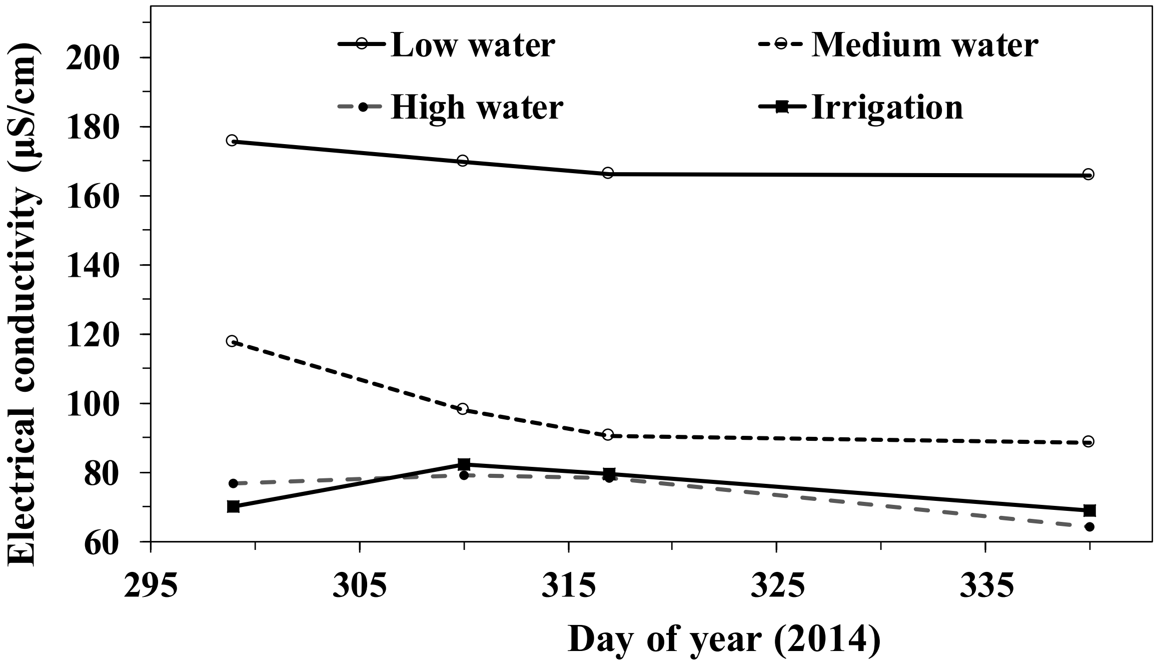

Figure 4.19 Comparison of electrical conductivity (EC) between low, medium, high watered treatments and irrigation water for day of year 299 to 340 (2014).

4.4 Analysis of economics

The common goal for commercial forestry nurseries is to produce sufficient good quality planting stock at the lowest possible cost. Semi-automated irrigation systems currently used in most forestry nurseries, such as a fixed timer-based system may irrigate well if managed correctly during peak water demands (Gravalos *et al*., 2007). However, they may waste water on cooler and cloudy days since these systems execute similar schedules regardless of weather and season. Although nursery managers can manually adjust these systems to cope with seasonal changes to the seedlings growth stages, this is not always done very efficiently. Most of these systems may also not alert the nursery manager if there is a problem with the irrigation system. Automated irrigation systems based on growing media water content measurements may address these challenges. However, they may be costly. Therefore, understanding their costs against the benefits they offer is important.

The cost-benefit analysis is a practical assessment of a need to implement a system by comparing the costs of implementation against its potential benefits and risks associated with not having such a system in place (Graham, 1981). For example, in a nursery, changing an irrigation system from a fixed timer-based system to a fully automated system may be very costly. However, such an automated irrigation system may irrigate seedlings very efficiently and provide savings on water costs (Belayneh *et al.*, 2013). Potential human error, such as incorrect setting of a timer system which may lead to loss of seedlings, may be eliminated in a fully automated system. In contrast, an efficient nursery manager may manage a fixed timer system well minimising under- and over-irrigation of seedlings but not if there are power or water interruptions over weekends for example.

4.4.1 Fully automated irrigation systems

There are many commercially available fully automated irrigation systems. The two commonly used systems in a nursery environment are a datalogger controller and a programmable logic controller (PLC) systems. Many researchers have successfully used these systems to measure soil water content and potential (Yoder *et al*., 1997; Baumhardt *et al.*, 2000; Gebregiorgis and Savage, 2006a; Lukanu and Savage, 2006; Nemali and van Iersel, 2006; Kizito *et al.*, 2008; van der Westhuizen, 2009; Belayneh *et al*., 2013). A datalogger controller is a device that initiates measurements using a sensor, processes data on board, records the data at specified intervals and controls external devices such as pumps (Campbell Scientific, 2015). Most dataloggers are rugged and independent of AC power. They usually use 12V DC power making them mobile and not prone to failure during Eskom load shedding.

A PLC system is a digital computer that has a processor, screen, keyboard and analog or digital input ports. It has a capacity to control sensors and other electrical devices such as water pumps through relay drivers. Additional input channels may be added. These controllers are also capable of recording data. The differences between fixed timer-based, datalogger and PLC systems is illustrated (Table 4.4).

Table 4.4 Comparison of irrigation controllers commonly used in nurseries.

	Fixed timer system	PLC controller	Datalogger controller
Support SDI-12[9]	N/A	Yes: requires a convertor	Yes
Power	220 VAC	220 VAC	12 VDC
Automation	Semi-automated	Fully automated	Fully automated
Advantages	Inexpensive Easy to program Simple to use	Water savings Improves plant growth No limit to input ports	Water savings Improves plant growth Offer early warning Rugged and mobile Inexpensive if using a basic system Not affected by power grid
Disadvantages	Tedious May waste water Does not offer early warning Not mobile	Expensive Does not interface with research grade sensors Require skilled personnel to program Use AC power (therefore backup power needed) Long delay time if there is a problem	May be expensive when using complex system Requires skilled personnel to program Limited control ports for cheapest dataloggers

[9] Serial Digital Interface at 1200 baud

4.4.2 Costs of a datalogger controlled irrigation system

The costs of implementing an automated irrigation system using a datalogger controller was conducted for a forestry research nursery over twelve months. These comparisons were conducted using the estimated costs for such a system as at July 2015 (R1.00 = $12.45). The datalogger control system may be divided into two: baseline and a complex system. The baseline system consist of a commercially available low cost CR200X datalogger with only two control ports, convertor, a sensor and a solenoid valve (Table 4.5). The cellphone modem may be added to the system to activate early warning in the form of an SMS or e-mail or TCP/IP protocols.

A Campbell CR1000 datalogger with eight communication ports may be used for a more complex system. A computer (PC), Campbell LoggerNet support software and Real-Time Monitor and Control software (Professional version) (RTMC Pro) are needed to display data in near real-time on the internet (www.campbellsci.com). This system is also capable of sending an SMS and/or e-mail notification to warn the nursery manager if there is a problem with the irrigation system. Costs of each system are presented in Table 4.5. Additional costs of programming and connecting the system should be accounted for.

Table 4.5 Equipment and costs (as at July 2015) needed for datalogger irrigation system.

Baseline system	Cost per item (R)	Complex system	Cost per item (R)
CR200X datalogger	6 160	CR1000 datalogger	19 200
220 VAC to 24 VDC convertor	300	220 VAC to 24 VDC convertor	300
Solenoid valve	320	Solenoid valve	320
EC-5 sensor	1 520	EC-5 sensor	1 520
Cellphone modem	2 050	PC	5 000
		LoggerNet software	7 700
		RTMC pro	7 900
Total	**10 350**		**41 940**

4.4.3 Benefits of a datalogger automated irrigation system

The initial costs of changing from a fixed timer-based system to a datalogger system may initially be high. However, the benefits such as savings of water, time and pumping costs may be achieved. In a study by Belayneh *et al*. (2013) on costs and benefits of an automated irrigation system, annual cost savings of (US) \$8 138, \$12 150 and \$20 288 for pumping, management and water savings costs, respectively, were achieved. A total water savings of 53.5% was achieved by completely switching from timer-based system to an automated irrigation system. Belayneh *et al*. (2013) estimated the time required to manage a fixed timer-based system at 5 h per week. The fully automated irrigation system reduced this time to 2 h per week. In a study by Nzokou *et al*. (2010) on automated irrigation system using drip irrigation, a significant reduction in labour requirements for managing the automated irrigation system improved the overall profitability of the farm. For this study, management of the irrigation system was significantly reduced since monitoring was mostly done online. Irrigation water savings could not be quantified since a fixed timer-based system was not included in the study. Significant irrigation and pumping costs reduction using fully automated systems have been reported by (Nemali and van Iersel, 2006; van der Westhuizen, 2009; Belayneh *et al*., 2013). Nemali and van Iersel (2006) reported other benefits such as a significant improvement in plant growth, robust plants, reduced leaching of nutrients, decrease in pests and diseases risks and a reduction in waterlogged conditions within the root zone. A high watered treatment in this study over-irrigated the seedlings and low electrical conductivity was recorded compared to other treatments. In contrast, the low watered treatment had a low nutrient leaching due to low water application. Nzokou *et al*. (2010) reported other benefits of an automated system as reduction in pollution of rivers, dams and groundwater.

The datalogger is capable of sending an alert to a nursery manager if there is a problem with an irrigation system. Savage (2014b, 2015) successfully tested an early warning system for the minimum grass temperature. An alert through an e-mail and File Transfer Protocol (FTP) could be sent to the systems manager. An SMS alert may also be possible through the use of an incoming e-mail to create a rule to SMS others of an equipment failure (Savage, 2014b).

For this study, irrigation was monitored online in near real-time. Measurements were visually displayed in the form of temporal graphs and scatter plots. Data were then easily examined and measurement trends and discrepancies were easily noticed. This monitoring avoided an experimental failure on two occasions in this study. Firstly, the water pump failed and seedlings were not irrigated and secondly an EC-5 sensor was pulled out of the seedling plug and the system continuously irrigated. These problems were spotted online and early interventions were possible. Such system may be a useful tool to offer a nursery manager the ability to observe changes in nursery conditions online in near real-time to allow for early intervention. Loss of seedlings may be prevented with consequential savings. Automated irrigation system may also offer ease of use and convenience.

The datalogger controlled systems work well for research and small scale applications due to the limited number of control channels available. Using this system in a large scale operation may significantly increase the implementation costs, but with reduced cost per unit area of crop. For large commercial applications, the mostly appropriate system could be a PLC.

4.5 Conclusion

Irrigation scheduling for *Eucalyptus* nursery stock was successfully controlled using Decagon EC-5 soil water content sensors. Changing irrigation scheduling from single pre-determined set points to using *LL* and *DUL* caused an improvement in irrigation scheduling. The sensors in the low watering treatment showed a slightly higher variation in measurements compared to the medium and high watering treatments. Generally, there was a large SE between sensors in each treatment at *DUL* and was less so at *LL*. Seedlings in the high watering treatment showed the highest root collar diameter, height and stomatal conductance followed by medium and low watering treatments. However, seedlings in the low watering treatment were hardier and more resistant to water stress. No significant differences were observed between the root-to-shoot ratio for the different treatments, but the high watering treatment had the greatest seedling mass and total leaf area. The high quantity of irrigation in the medium and high watering treatment washed off nutrients in the growing media as indicated by the low EC for these treatments. Analysis of economics showed that the initial costs of changing from fixed timer-based to automated irrigation system are high. However, long term benefits such as reduction in water use and management time can be achieved. This system further offers an early warning to the user if there is a problem with an irrigation system

In summary, the results for this study have shown that the low cost Decagon EC-5 soil water content sensors may be used to schedule irrigation in containerised nursery trays with small cavity volumes. Furthermore, such system may be useful for conducting studies where it is necessary to have more detailed information on the water status of the media at different periods or may be useful for controlling irrigation more carefully where it is necessary to have treatments with different levels of irrigation (such as in drought stress studies). These results also illustrate how over-irrigation of seedlings can increase their susceptibility to water stress, increase the leaching of nutrients from the growing media and waste irrigation water.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

5.1 Overall conclusions

Commercial forestry nurseries mostly use a fixed timer-based irrigation scheduling method to irrigate planting stock. However, this system does not account for changes in plant water use caused by changes in solar irradiance, air temperature and relative humidity (RH), or the growth phase of the plants. This commonly leads to over-irrigation of seedlings causing leaching of nutrients, water wastage, creating an environment for pests and diseases and seedlings that are not well hardened off. An efficient irrigation scheduling method may be achieved by accurately measuring the growing media water content and replenishing the depleted water using an automated system.

The main focus of the study was to evaluate an automated soil water content irrigation scheduling system using drained upper and lower soil water content limits. Capacitance sensors were used to control irrigation for *Eucalyptus* planting stock subjected to different water regimes. Growth and development of *Eucalyptus* planting stock was then compared to understand the morphological and physiological response to different irrigation levels.

The low cost commercially available Decagon EC-5 soil water content sensors were calibrated against the gravimetric method using different nursery growing media. The specific growing media calibration equation was then used to schedule irrigation for *Eucalyptus* planting stock grown in seedling trays inside a greenhouse. The sensors were calibrated for four growing media: CP, CPBV, PB and sandy soil. Irrigation was scheduled for low, medium and high watering treatments in a fully air temperature controlled greenhouse. The daily applied irrigation and total drainage per treatment was measured. Microclimate measurements inside the greenhouse were solar irradiance, air temperature and RH with hourly grass reference evaporation (ETo) estimated and compared with that for an open area UKZN AIM system. The greenhouse microclimate and sensor measurements were displayed and shared on a web-based information system.

As part of a calibration process, three commercially available dielectric (model EC-5) sensors measuring soil water content in the same growing media were compared with soil water status varying from dry to saturated. Sensor comparison showed reasonably good agreement at low soil water content. However, the agreement decreased with increase in soil water content. Poor contact between sensor and the growing media caused by re-packing of the media during the calibration process was probably the major cause for the differences. It was concluded that sensor measurement differences at high soil water content were above the drained upper limit and did not influence the measurement of soil water content in the plant available water (*PAW*) range.

Calibration results showed a linear relationship between sensor output and gravimetric water content for all four growing media. For all growing media R^2 was greater than 0.92. Evaluation of the manufacturer supplied calibration equation showed poor estimation of soil water content, mostly over- and under- estimating at high and low soil water content, respectively. The laboratory calibration was 11 to 20% more accurate than the manufacturer supplied calibration equation. This inaccuracy exceeded the manufacturer specified 5% error if soil specific calibration is not done. However, over- and under estimation did not affect soil water content measurements in the *PAW* range. For the greenhouse, air temperature was maintained below 25° C whilst the solar irradiance was 60% lower than the outside. The greenhouse RH was consistently higher compared to outside and the greenhouse ETo measurements were 50% lower that the outside.

Irrigation scheduling was programmed at a single set point for Experiment 1 using GxU hybrid clones. The cuttings were irrigated too frequently for a short duration. For the low watering treatment, under-watering occurred, because irrigation was not evenly distributed throughout the seedling trays. This was evident by wilting of seedlings within a tray even after irrigation. The medium and high watering treatments were over-watered which led to continuous draining of seedling trays. The over- and under- watering challenges were addressed in Experiment 2 using lower and drained upper soil water content limits where *E. dunnii* seedlings were used. A large standard error (SE) in sensor measurements was observed in the low watering treatment. This was probably due to poor media-to-sensor contact and the change in pore space volume from wet to dry media. Sensor measurements in the medium and high watering treatments showed reasonably good agreement. However, for all treatments a high SE was observed at the drained upper limit and decreased at the lower limit, indicating that sensor accuracy decreased with increase in growing media water content. The irrigation system automatically addressed the seasonal and plant growth water demand differences without adjustment to the datalogger program. For example, in winter when the seedlings were younger the low watering treatment was watered every second day whereas medium and high watering treatment were watered daily. In summer, due to an increase in air temperatures and increase in seedling size, the low watering treatment was watered daily whereas the medium and high watering treatments were watered twice a day. The high watering treatment irrigated more frequently in small quantities, whereas the medium watering treatment irrigated less frequently for slightly longer duration. This led to these treatments applying almost the same quantity of water per day.

Growth of *E. dunnii* seedlings subjected to low, medium and high watering regimes were compared. Seedling root collar diameter (RCD), height and root-to-shoot ratio were compared. Low watering treatment seedlings had the lowest average RCD and heights followed by medium and high watering treatments. The low growth in the low watering treatment was most likely due to the low soil water content. No significant differences were observed in the root-to-shoot ratio between treatments. This suggests that although the volume of roots in the low watering treatment was small, they were enough to supply seedling leaves with water they needed. Similarly, high watering treatment had a slightly greater root volume to supply sufficient water to larger shoots.

The low watering treatment seedlings were hardier and more resistant to water stress. This was evident on day of year 276 (2014), when the water pump broke down and there was no irrigation for the whole day. The high watering treatment plants were the first to show signs of water stress followed by the medium watering treatment. No water stress signs were observed for the low watering treatment. Seedlings in the low watering treatment are more likely to survive better under field conditions.

Stomatal conductance (g_s) for seedlings subjected to low, medium and high watering treatments was compared. The g_s for the high watering treatment was consistently greater throughout the study followed by medium and low watering treatments. This showed that transpiration rates in the high watering treatment were the highest for all treatments. The RH inside the greenhouse was greater than 60% during the day and 100% at night. At times when the RH was at its highest, stomatal opening may have decreased. Seedlings were diagnosed with oedema which was most probably caused by the high RH inside the greenhouse. This condition caused severe damage to seedlings foliage which may have reduced stomatal opening.

The total daily drainage and EC was measured per treatment and compared. The high watering treatment had the highest daily average drainage followed by medium and low watering treatments. As expected, the highest EC was measured in the low watering treatment. The lowest EC in the high watering treatment was most likely caused by excessive irrigation which leached nutrients from the growing media. However, high watering is sometimes necessary to wash off excessive salt build up in the growing media.

For this study, the analysis of economics indicated that implementing this system could be costly, especially if a complex system is used. However, long term benefits such as water and management time savings could potentially be achieved. The risks associated with planting stock loss could be avoided with the use of an early warning system. The web-based system was successfully used to display and share the greenhouse microclimatic data and media water content measurements in near real-time for this study. This was a very useful tool for evaluating the different watering regimes and the display was used as an early warning system in identifying problems in the greenhouse. Problems such as lack of irrigation due to pump breakdown and continuous irrigation caused by a sensor dislodged from its seedling plug were swiftly identified and attended to.

In this study, commercially available Decagon EC-5 soil water content sensors were successfully used to control irrigation for *E. dunnii* seedlings under different watering regimes. Specific growing media calibration was necessary to increase measurement accuracy. While most calibration procedures are cumbersome and time consuming, the calibration procedure used in this study was easy to set up and time saving since the manufacturer recommended calibrating one sensor and using the calibration equation for all other sensors. Low watering treatment seedlings were more robust, hardier and resistant to water stress compared to those in the medium and high watering treatments. Consistent lower stomatal conductance may mean these seedlings transpired less thereby conserving water. These seedlings may have the potential to survive and grow well under field conditions compared to seedlings in other treatments. In addition, the low watering treatment used 40% less water compared to other treatments.

5.2 Recommendations for future research

The use of a web-based soil water content measurement and control system for irrigation of *Eucalyptus* planting stock provided a better understanding of fully automated nursery irrigation using the latest sensor technology. Most commercial forestry nurseries are semi-automated, using a timer-based system. With the challenges of the timer system, a fully automated irrigation system may add value and provide new opportunities for improving management of irrigation in forestry nurseries.

Future research could involve a repetition of the study on other *Eucalyptus* species on a larger scale. This will enable a thorough understanding of how different species or clones behave under different water regimes. For example, some species have larger canopy cover which might block irrigation water from reaching the growing media. The study could also be conducted in a semi-open structure since most commercial forestry nurseries use more open structures to grow their planting stock. This will add practical value to the forestry industry. Once the seedlings are ready for the field, they could be planted in the field to compare their growth rates and field survival.

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APPENDIX A: A PROGRAM USED WITH CAMPBELL SCIENTIFIC CR1000 DATALOGGER TO MEASURE AND CONTROL IRRIGATION

```
'CR1000
'Created by Short Cut (3.0)

'Declare Variables and Units
Public BattV
Public PTemp_C
Public Day_of_year – not used
Public VW
Public VW_2
Public VW_3
Public VW_4
Public VW_5
Public VW_6
Public VW_7
Public VW_8
Public VW_9
Public VW_10
Public VW_11
Public VW_12
Public AirTC
Public RH
Public SlrkW
Public SlrkJ
Public Rain_WS1
Public Rain_WS2
Public Rain_WS3
Public rTime(8)
Public Flag(8) As Boolean
Public Time_SprinkleWS1
Public Time_SprinkleWS2
Public Time_SprinkleWS3

Units Time_SprinkleWS1=min
Units Time_SprinkleWS2=min
Units Time_SprinkleWS3=min
Units BattV=Volts
Units PTemp_C=Deg C
Units AirTC=Deg C
Units RH=%
Units SlrkW=kW/m^2
Units SlrkJ=kJ/m^2
Units Rain_WS1=mm
Units Rain_WS2=mm
Units Rain_WS3=mm
```

```
'Define Data Tables
DataTable(Icfr2min,True,-1)
DataInterval(0,2,Min,10)
 Minimum(1,BattV,FP2,False,False)
 Average(1,VW,FP2,False)
 Average(1,VW_2,FP2,False)
 Average (1,VW_3,FP2,False)
 Average(1,VW_4,FP2,False)
 Average(1,VW_5,FP2,False)
 Average(1,VW_6,FP2,False)
Average(1,VW_7,FP2,False)
Average(1,VW_8,FP2,False)
Average(1,VW_9,FP2,False)
Average(1,VW_10,FP2,False)
Average(1,VW_11,FP2,False)
Average(1,VW_12,FP2,False)
Average(1,AirTC,FP2,False)
Sample(1,RH,FP2)
Average(1,SlrkW,FP2,False)
Totalize(1,Rain_WS1,FP2,False)
Totalize(1,Rain_WS2,FP2,False)
Totalize(1,Rain_WS3,FP2,False)
Totalize (1,Time_SprinkleWS1,FP2,False)
Totalize (1,Time_SprinkleWS2,FP2,False)
Totalize (1,Time_SprinkleWS3,FP2,False)
EndTable

DataTable(Icfr60min,True,-1)
DataInterval(0,60,Min,10)
Minimum(1,BattV,FP2,False,False)
Maximum(1,BattV,FP2,False,False)
Average(1,VW,FP2,False)
Average(1,VW_2,FP2,False)
Average(1,VW_3,FP2,False)
Average(1,VW_4,FP2,False)
Average(1,VW_5,FP2,False)
Average(1,VW_6,FP2,False)
Average(1,VW_7,FP2,False)
Average(1,VW_8,FP2,False)
Average(1,VW_9,FP2,False)
Average(1,VW_10,FP2,False)
Average(1,VW_11,FP2,False)
Average(1,VW_12,FP2,False)
Average(1,AirTC,FP2,False)
Sample(1,RH,FP2)
Average(1,SlrkW,FP2,False)
ETsz(AirTC,RH,0,SlrkW,360,0,0,3,0,FP2,False)
'FieldNames("ETos,Rso")
Totalize(1,Rain_WS1,FP2,False)
Totalize(1,Rain_WS2,FP2,False)
Totalize(1,Rain_WS3,FP2,False)
Totalize (1,Time_SprinkleWS1,FP2,False)
Totalize (1,Time_SprinkleWS2,FP2,False)
```

```
Totalize (1,Time_SprinkleWS3,FP2,False)
EndTable

DataTable(Icfrdaily,True,-1)
DataInterval(0,1440,Min,10)
Minimum(1,BattV,FP2,False,False)
Maximum(1,BattV,FP2,False,False)
Average(1,VW,FP2,False)
Average(1,VW_2,FP2,False)
Average(1,VW_3,FP2,False)
Average(1,VW_4,FP2,False)
Average(1,VW_5,FP2,False)
Average(1,VW_6,FP2,False)
Average(1,VW_7,FP2,False)
Average(1,VW_8,FP2,False)
Average(1,VW_9,FP2,False)
Average(1,VW_10,FP2,False)
Average(1,VW_11,FP2,False)
Average(1,VW_12,FP2,False)
Average(1,AirTC,FP2,False)
Sample(1,RH,FP2)
Average(1,SlrkW,FP2,False)
ETsz(AirTC,RH,0,SlrkW,360,0,0,3,0,FP2,False)
FieldNames("ETos,Rso")
Totalize(1,Rain_WS1,FP2,False)
Totalize(1,Rain_WS2,FP2,False)
Totalize(1,Rain_WS3,FP2,False)
Totalize (1,Time_SprinkleWS1,FP2,False)
Totalize (1,Time_SprinkleWS2,FP2,False)
Totalize (1,Time_SprinkleWS3,FP2,False)
EndTable

'Main Program
BeginProg
'Main Scan
Scan(1,Sec,10,0)
'Default Datalogger Battery Voltage measurement 'BattV'

' RealTime(rTime)
Day_of_year=rTime(8)+rTime(4)/24+rTime(5)/(60*24)+rTime(6)/(60*60*24)+rTime(7)/(1000000*6
0*60*24)-1 – not used

Battery(BattV)
'Default Wiring Panel Temperature measurement 'PTemp_C'
PanelTemp(PTemp_C,_50Hz)
'ECHO Probe EC-5 measurement VW:
BrHalf(VW,1,mV2500,1,1,1,2500,False,10000,_50Hz,3.25,-0.3115)
'ECHO Probe EC-5 measurement VW_2:
BrHalf(VW_2,1,mV2500,2,1,1,2500,False,10000,_50Hz,3.25,-0.3115)
'ECHO Probe EC-5 measurement VW_3:
BrHalf(VW_3,1,mV2500,3,1,1,2500,False,10000,_50Hz,3.25,-0.3115)
'ECHO Probe EC-5 measurement VW_4:
BrHalf(VW_4,1,mV2500,4,1,1,2500,False,10000,_50Hz,3.25,-0.3115)
```

```
'ECHO Probe EC-5 measurement VW_5:
BrHalf(VW_5,1,mV2500,5,2,1,2500,False,10000,_50Hz,3.25,-0.3115)
'ECHO Probe EC-5 measurement VW_6:
BrHalf(VW_6,1,mV2500,6,2,1,2500,False,10000,_50Hz,3.25,-0.3115)
'ECHO Probe EC-5 measurement VW_7:
BrHalf(VW_7,1,mV2500,7,2,1,2500,False,10000,_50Hz,3.25,-0.3115)
'ECHO Probe EC-5 measurement VW_8:
BrHalf(VW_8,1,mV2500,8,2,1,2500,False,10000,_50Hz,3.25,-0.3115)
'ECHO Probe EC-5 measurement VW_9:
BrHalf(VW_9,1,mV2500,9,3,1,2500,False,10000,_50Hz,3.25,-0.3115)
'ECHO Probe EC-5 measurement VW_10:
BrHalf(VW_10,1,mV2500,10,3,1,2500,False,10000,_50Hz,3.25,-0.3115)
'ECHO Probe EC-5 measurement VW_11:
BrHalf(VW_11,1,mV2500,11,3,1,2500,False,10000,_50Hz,3.25,-0.3115)
'ECHO Probe EC-5 measurement VW_12:
BrHalf(VW_12,1,mV2500,12,3,1,2500,False,10000,_50Hz,3.25,-0.3115)
'HC2S3 (constant power) Temperature & Relative Humidity Sensor measurements 'AirTC' and 'RH'
VoltSe(AirTC,1,mV2500,13,0,0,_50Hz,0.1,-40)
VoltSe(RH,1,mV2500,14,0,0,_50Hz,0.1,0)
If RH>100 AND RH<103 Then RH=100
'CM3 Pyranometer (CSL) measurements 'SlrkJ' and 'SlrkW'
VoltDiff(SlrkW,1,mV25,8,True,0,_50Hz,1,0)
If SlrkW<0 Then SlrkW=0
SlrkJ=SlrkW*0.5834306
SlrkW=SlrkW*116.6861
'Generic Tipping Bucket Rain Gauge measurement 'Rain_mm'
PulseCount(Rain_WS1,1,1,2,0,0.254,0)
'Generic Tipping Bucket Rain Gauge measurement 'Rain_mm_2'
PulseCount(Rain_WS2,1,2,2,0,0.254,0)
'Generic Tipping Bucket Rain Gauge measurement 'Rain_mm_3'
PulseCount(Rain_WS3,1,11,2,0,0.1,0)
'Alarm w/ Silence Alarm Flag
'           If rTime(4)>1 AND rTime(4)+rTime(5)/60<23
If Flag(1)=0 Then
If (((VW+VW_2+VW_3+VW_4)/4)< 0.22) Then
PortSet(2,1)
Flag(2)=1
Else
If Flag(2)=0
PortSet(2,0)
EndIf
EndIf

If (((VW_5+VW_6+VW_7+VW_8)/4)<0.26) Then
PortSet(3,1)
Flag(3)=1
Else
If Flag(3)=0
PortSet(3,0)
EndIf
EndIf

If (((VW_9+VW_10+VW_11+VW_12)/4)<0.32) Then
```

```
PortSet(4,1)
Flag(4)=1
Else
If Flag(4)=0 Then
PortSet(4,0)
EndIf
EndIf

If (RH<60) Then
PortSet(5,1)
Else
PortSet(5,0)
EndIf
EndIf

If (((VW+VW_2+VW_3+VW_4)/4)> 0.26) Then
Flag(2)=0
EndIf

If (((VW_5+VW_6+VW_7+VW_8)/4)>0.32) Then
Flag(3)=0
EndIf

If (((VW_9+VW_10+VW_11+VW_12)/4)>0.41) Then
Flag(4)=0
EndIf

'Call Data Tables and Store Data
CallTable(Icfr2min)
CallTable(Icfr60min)
CallTable (Icfrdaily)
NextScan
EndProg
```